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(FINAL REPORT)

SHARED SPECTRUM DISPLAY ENHANCEMENT

TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-64-673

JANUARY 1965

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Ann R. Bien

DECISION SCIENCES LABORATORY
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

(Prepared under Contract No. AF 19 (628)-3882 by the
Ground Systems Group, Hughes Aircraft Company, Fullerton, California.)

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ABSTRACT

An illumination system is described which utilizes for display, portions of the visible spectrum which have been excluded from the ambient light. The resulting tinted illumination is matched in brightness to a standard white light by experimental subjects, and stimulus threshold measurements made as a function of display intensity for various stimulus and ambient spectra. Certain combinations are found to lower the threshold of detection, indicating enhanced stimulus brightness, whereas others are found to raise the threshold. A close relationship is found between experimental data and results predicted on the basis of previously published increment-threshold measurements.

PUBLICATION REVIEW AND APPROVAL

This Technical Documentary Report has been reviewed and is approved.

FOR THE COMMANDER

Donald W Connolly

DONALD W. CONNOLLY
Chief, Display Division
Decision Sciences Laboratory

Roy Morgan

ROY MORGAN
Colonel, USAF
Director, Decision Sciences Laboratory

FOREWORD

The work reported herein was accomplished at Ground Systems Group, Hughes Aircraft Company, Fullerton, California under Contract No. AF-19(628)-3882. It was performed in the Human Factors Laboratory by personnel of the Human Factors Section, Systems Effectiveness Department, Product Effectiveness Division.

The Hughes Aircraft Company reference number for this report is: FR-65-10-30.

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SHARED SPECTRUM DISPLAY ENHANCEMENT

I. INTRODUCTION

As radar and other cathode-ray tube displays are encountered more and more frequently as components of highly varied operational centers, rather than as the sole occupants of the World War II "radar room," lighting systems developed specifically for the radar console environment become progressively less satisfactory. Dense personnel traffic, a multitude of transilluminated status and wall displays, and the need for color coding of control and display surfaces gainsay the advantages of monochromatic selective spectrum lighting[1,15] which is usually dim, precludes reflective color coding, and which many people find subjectively unpleasant. White light, on the other hand, has been shown to cause a significant decrement in cathode-ray tube visibility with as little as one footcandle illumination level[3]. It would be highly desirable to be able to provide general overhead illumination which would retain advantages for viewing cathode-ray tube and other console displays, while at the same time offering a natural-appearing light of satisfactory brightness and chromatic content.

The present study comprises an evaluation of one embodiment of a lighting technique which holds promise of meeting the above requirements. Called "shared-spectrum display enhancement," it is the exact converse of methods which utilize narrow portions of the visible spectrum for ambient illumination; instead, a narrow band of wavelengths is <u>removed</u> from the illuminant, in the expectation that the observer will be sensitized to the excluded colors. This concept was first suggested to these investigators by Mr. Paul Mooney, of North American Aviation.

There are several ways in which this can be done. In the simplest case, a single narrow band would be removed from the ambient illumination and reserved for display. Chromatic brightness enhancement should then obtain for any display whose dominant wavelength falls in the omitted band. The fact that only one display band is available, however, would greatly restrict the number of phosphors or projected display hues that would be aided by the system. Due to the narrow excluded band, the ambient illumination would be tinted. However, since only a small segment of the normal white light is absent, most color coding capability would be retained, and operators would quickly adapt to an illuminant of such low saturation[2].

Even if the excluded spectral band were broad, however, it would still be possible to provide a white-appearing illuminant and sufficient chromaticity for the use of color coding in reflected displays. Table I shows several complementary pairs of wavelengths from the continuum of complementary colors[16]; if the dominant wavelengths of the remaining bands are complementary and their intensities are in the correct ratio, the results will be white light.

Table I. Representative Complementary Wavelength Pairs

λ	λ'
460	572.4
470	574.7
480	580.4
490	600.0
570	427.4
580	479.6
590	486.8
600	490.0
610	491.7

There is therefore a real prospect of being able to provide a psychologically white ambient illumination which (1) will not contaminate cathode-ray tube displays equipped with a corresponding filter, (2) will allow comprehensive color coding of reflective displays, and (3) will engender a subjective intensification of colors whose dominant wavelengths fall within the rejected band. The first two points are clear from the physical nature of the proposed illumination; evaluation of the third is the purpose of this study.

II. BACKGROUND

There is good reason to expect a subjective intensification of colors which are removed from the ambient spectrum. For one thing, such colors are clearly complementary to the remaining ambient (complementary lights are defined as lights which mix to form white), and it has long been recognized that adaptation to colored light results in increased luminous sensitivity to the complement[21]; indeed, Hurvich and Jameson[13] found that adaptation to a given wavelength depressed the luminosity function

in that area of the spectrum and augmented it everywhere else, -- not just in the region of the complementary color. Kohler[14] postulated an adaptive reference level which he called a "null point," from which differential stimuli depart.

More recently, however, there has been an increasing tendency to explain visual adaptive phenomena in terms of retinal photochemistry and relatively simple visual mechanisms. Le Grand[17] summed this up in the observation that, although experimental tri-variance of vision requires at least three types of receptors, "any number *n* is mathematically possible if we suppose *n - 3* additional relationships between the *n* responses." He went on to suggest a small number of visual pigments distributed randomly among the entire population of cones. This idea is also advanced on a theoretical basis by Hunt[12], who cites the constancy of metameric matches (metamers are identical-appearing colors having different spectral compositions) and the additivity of color matches as evidence that the spectral sensitivity functions of the retinal receptors must be any linear combination of three basic sensitivity functions, possibly including a "white" sensitivity curve representing the sum of the three components. There is some physiological background to such a concept in the dominator-modulator" theory of Granit[8], which he based on recordings of the electrical responses of single and grouped optic nerve fibers and ganglia in response to exposure to light of different wavelengths. Crudely paraphrased, it was his idea that luminosity or brightness is an independent sensation (dominator), accompanied by a complex of sensations signifying hue (modulator), and that these functions occur at the retinal level. Substantiation of the latter thesis is to be found in the four signal-processing mechanisms demonstrated by Lettvin *et al*[18] in the retinal ganglion of the frog.

Phototropic, phototactic, and visual reactions in both plants and animals nearly always involve a singular family of chemicals called *carotenoids*[4]; pigments formed from this group either alone or as prosthetic groups of proteins have absorption spectra with maxima occurring throughout the visible spectrum. Except for *rhodopsin* (visual purple) and its related products, considerable doubt affixes to the nature of visual pigments in the human eye, and to their breakdown and regeneration cycles during and after exposure to light. The number of visual pigments which have been identified in other organisms is impressive, however: Morton and Pitt[19] list eighteen, and Wald[22] has developed a system of retinene-opsin synthesis for an arbitrary number of visual pigments.

The significance to the present study of this body of research is clear. If the observer's response to colored light obeys

a dominator-modulator type of function, then the relatively slight change in luminosity occasioned by the withdrawal from the ambient illumination of a small spectral band can be expected to yield a negligible increase for colors located within that band. If there are exactly three light-sensing mechanisms of comparable sensitivity, responding maximally to three different wavelengths of light respectively, then that illumination system will succeed best which selectively adapts two of the mechanisms to the colored ambient light, leaving the third in a state of comparative dark adaptation. If there is a multiplicity of such receptors with sensitivity peaks throughout the spectrum (in apparent violation of Hunt's thesis), then the shared-spectrum technique will be generally valid at any point in the visible spectrum.

Two recent investigations lend heavy experimental support to the second speculation, -- that there is a small number of receptors which must be dealt with specifically by a successful illumination system. By continuously adapting the eye to one wavelength and measuring the luminosity curve as a function of the wavelength and intensity of the adapting stimulus, Stiles[20] has produced evidence of five independent receptor systems which he terms "pi-mechanisms." A modification of Stiles' method employed by Wald[23] comprises adaptation to a high-intensity spectral band, rather than to relatively low-intensity monochromatic light, and the subsequent luminosity determination. By selectively adapting the fovea to yellow, purple, and blue light, Wald has plotted action spectra for the blue, green, and red receptors, respectively, of two observers, finding peaks of luminous sensitivity at 430mμ , 540mμ , and 575mμ . These data, which conform closely to the corresponding Stiles pi-mechanisms, have also been extrapolated to the retinal level by allowing for absorption of the optical media and the macula lutea. If chromatic adaptation can be explained on this basis, then the spectral sensitivity devolving from a shared-spectrum ambient visual environment should be closely related to the integral of the product of the ambient spectrum and the difference, as a function of wavelength, between the spectra of the receptor(s) we wish to light-adapt and the spectra of the receptor(s) we wish to dark-adapt and thus sensitize. A weighting function derived from the Wald results is presented in the Analysis section of this report, where the topic is enlarged upon in connection with the experimental results of this study.

III. THE PRESENT EXPERIMENT

If a human observer has a lower detection threshold for a given stimulus in the presence of an experimental illuminant than in the presence of an equally bright white illuminant, the experimental illuminant may then be said to enhance stimulus brightness. The general types of spectral response to be considered for the stimulus and for the illuminant are diagrammed in Figure 1.

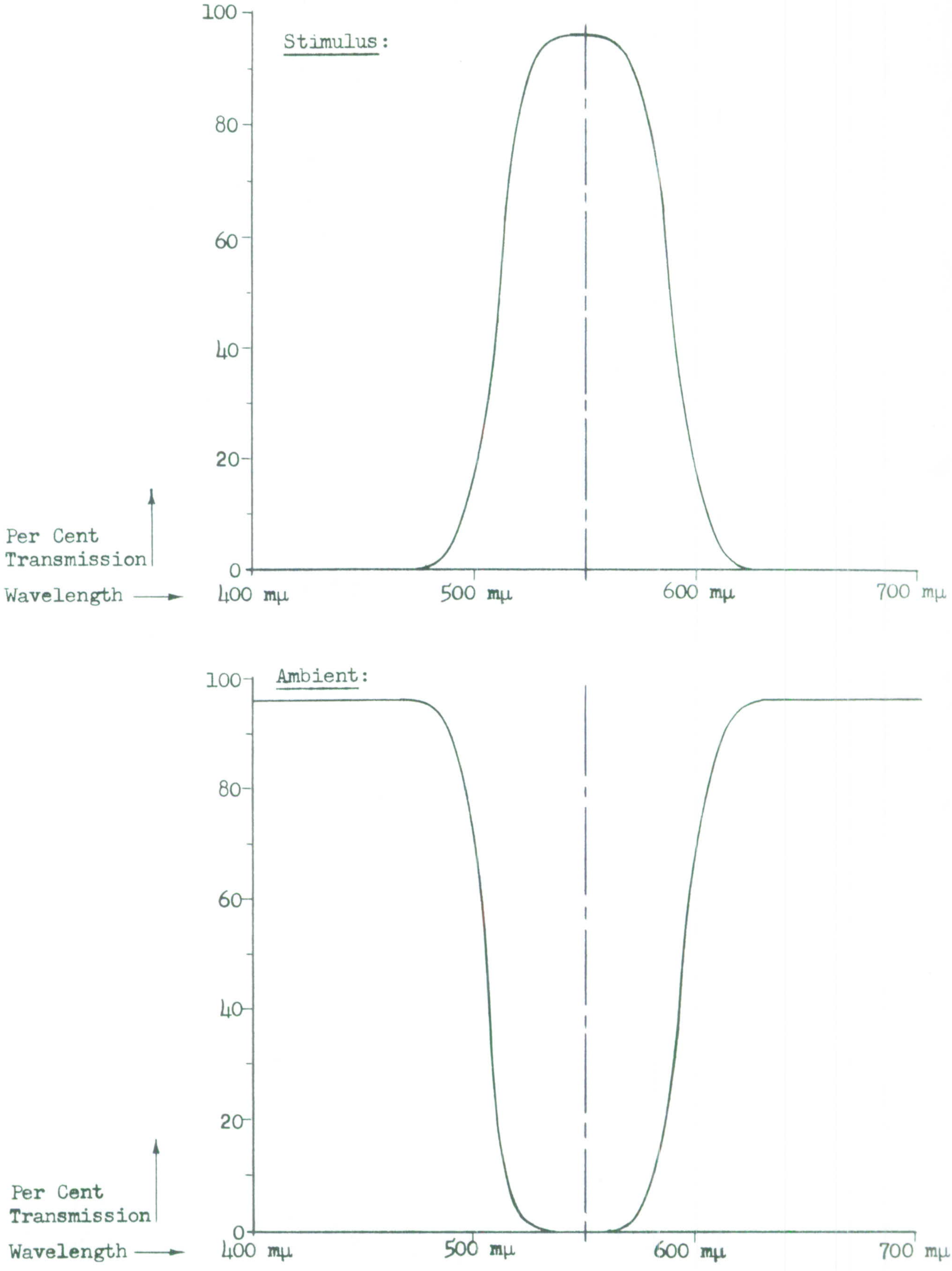

Figure 1. Typical stimulus and illuminant spectral response curves.

In order to understand how the physical parameters of the ambient illumination and the stimulus jointly affect brightness enhancement, and to provide some guidelines for ambient illumination design and further experimentation, the study has been designed to measure detection threshold as a function of the bandwidths of the stimulus and of the ambient notch, both independently and interactively. Stimulus and ambient background illumination are projected additively to a rear-projection screen from separate slide projectors; the spectral characteristics of each are determined by a pair of sharp-cutting dichroic filters.

Because a major limitation in the design of the experiment devolves from the finite slope of the dichroic filter cut, it is necessary to digress upon this point. Dichroic filters do not possess infinite slope, although they are superior to absorption filters in that respect. Inasmuch as our laboratory devices have slopes ranging from 11 mμ to 28 mμ (details of the dichroic filter set are given in Appendix I), we shall consider a 20 mμ slope in this discussion. Given a filter slope of 20 mμ, then, the smallest stimulus passband which will allow unattentuated transmission of the central wavelength is 20 mμ (see Figure 2). Similarly, the smallest ambient passband into which this stimulus can be inserted without common spectral transmission is 60 mμ.

In this study, we are interested in the effects of specific bandwidths of both stimulus and ambient. In addition, we cannot dismiss the possible importance of relational parameters; that is, we should like to know what happens at each stimulus bandwidth, for instance, when (a) the stimulus bandwidth is significantly less than the ambient bandwidth, (b) the stimulus bandwidth is the same as the ambient bandwidth, and (c) the stimulus bandwidth is significantly greater than the ambient bandwidth.

For any central wavelength let us denote conditions (a), (b), and (c) by -2, 0, and +2, and small, medium, and large bandwidths by 3, 5, and 7, respectively. Consider then a tabulation of all combinations of three conditions each of absolute stimulus and ambient bandwidths:

Table II. Relative Bandwidth as a Function of Absolute Bandwidth

	Ambient Bandwidth:	3	5	7
Stimulus Bandwidth	3:	0	-2	-4
	5:	+2	0	-2
	7:	+4	+2	0

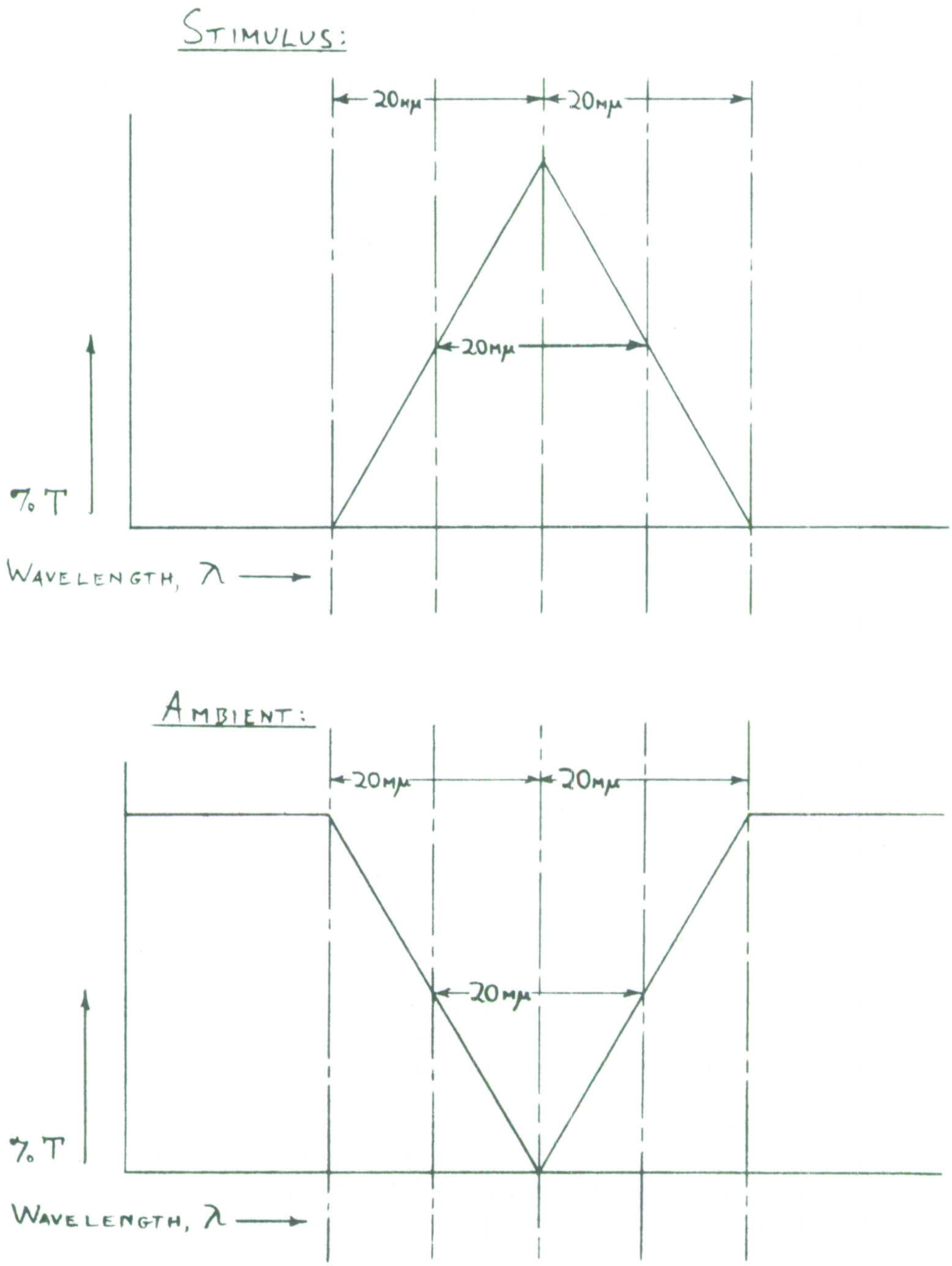

Figure 2. Smallest bandpass characteristic.

This is clearly an incomplete design in terms of relative variables. For an ambient bandwidth of three units, there are no cases in which the stimulus bandwidth is less than the ambient bandwidth, one case in which the two are equal, and two cases in which the stimulus bandwidth is greater than the ambient bandwidth. For an ambient bandwidth of five units, each of the three conditions is represented once; and, for an ambient bandwidth of seven units, the converse of the first case obtains. Two other orderings of the three variables in three-by-three designs are shown in Tables II and III, with each resulting in missed data.

Table III. Ambient Bandwidth as a Function of Relative and Stimulus Bandwidth

	Stimulus Bandwidth:	3	5	7
Relative Bandwidth	-2:	5	7	9
	0:	3	5	7
	+2:	1	3	5

Table IV. Stimulus Bandwidth as a Function of Relative and Ambient Bandwidth

	Ambient Bandwidth:	3	5	7
Relative Bandwidth	-2:	1	3	5
	0:	3	5	7
	+2	5	7	9

Table II for instance, presents all the relative conditions at all proposed stimulus bandwidths; but there are no -2's at an ambient bandwidth of 3, nor any +2's at 7. Although all relative conditions are to be found with each ambient bandwidth in Table III, there are no -2's at a stimulus bandwidth of 7, nor any +2's at a stimulus bandwidth of 3. From this it can be seen that, in order to complete the design given in Table I for relative as well as absolute variables, it is necessary to add to that table two more data points about the ends of the major diagonal, -- four points in all. Such a design is given in Table V, in which it will be noted that subsets of Table V may be taken to form Tables II (solid line), III (small dashed line), and IV (large dashed line). Five stimulus conditions under white light are also shown, for a total of eighteen treatments per subject per central wavelength.

Table V. Complete Design

Stimulus Bandwidth \ Ambient Bandwidth:	1	3	5	7	9	White
1:		-2				x
3:	+2	0	-2	-4		x
5:		+2	0	-2		x
7:		+4	+2	0	-2	x
9:				+2		x

It is interesting to consider the significance of the diagonals of Table V. All of the treatments along the major diagonal exhibit the small amount of spectral overlap characterized by having the stimulus and ambient bandwidths equal. Above the major diagonal, all conditions have the stimulus bandwidth less than the ambient bandwidth; below it, severe overlap results in a large spectral region in common between stimulus and ambient light. The degree of overlap then, increases as we move down across the positive diagonals, regardless of absolute stimulus and ambient bandwidth. Similarly, moving across the columns increases ambient bandwidth regardless of stimulus bandwidth; and moving across the rows increases stimulus bandwidth. Hence, there is available the appropriate data to regard any of the three quantities as the independent variable.

As will be noted from Table V, in order to acquire data which will permit analysis of three states each of absolute and relative bandwidths of the two main variables, five values are required of each, rather than three.

It was shown that the smallest bandwidth consistent with either unattentuated transmission (in the case of the stimulus) or full rejection (in the case of the ambient notch) of the central wavelength is the same as the length of the filter cut, -- 20 mμ; Figure 2 illustrated such a narrow-band filter response. If this curve is taken to represent the spectral response of the narrowest stimulus, then succeeding values for stimuli 3, 5, 7, and 9 may be developed as shown in Figure 3.

Consider the case where a stimulus is presented against ambient illumination having a notch of the same bandwidth (Figure 4). Because light of wavelengths falling along the two cuts is transmitted by both filter combinations, mutual contamination is present. Although this is obviously unavoidable in the "0" situation, wherein we have stated that stimulus and ambient bandwidths shall

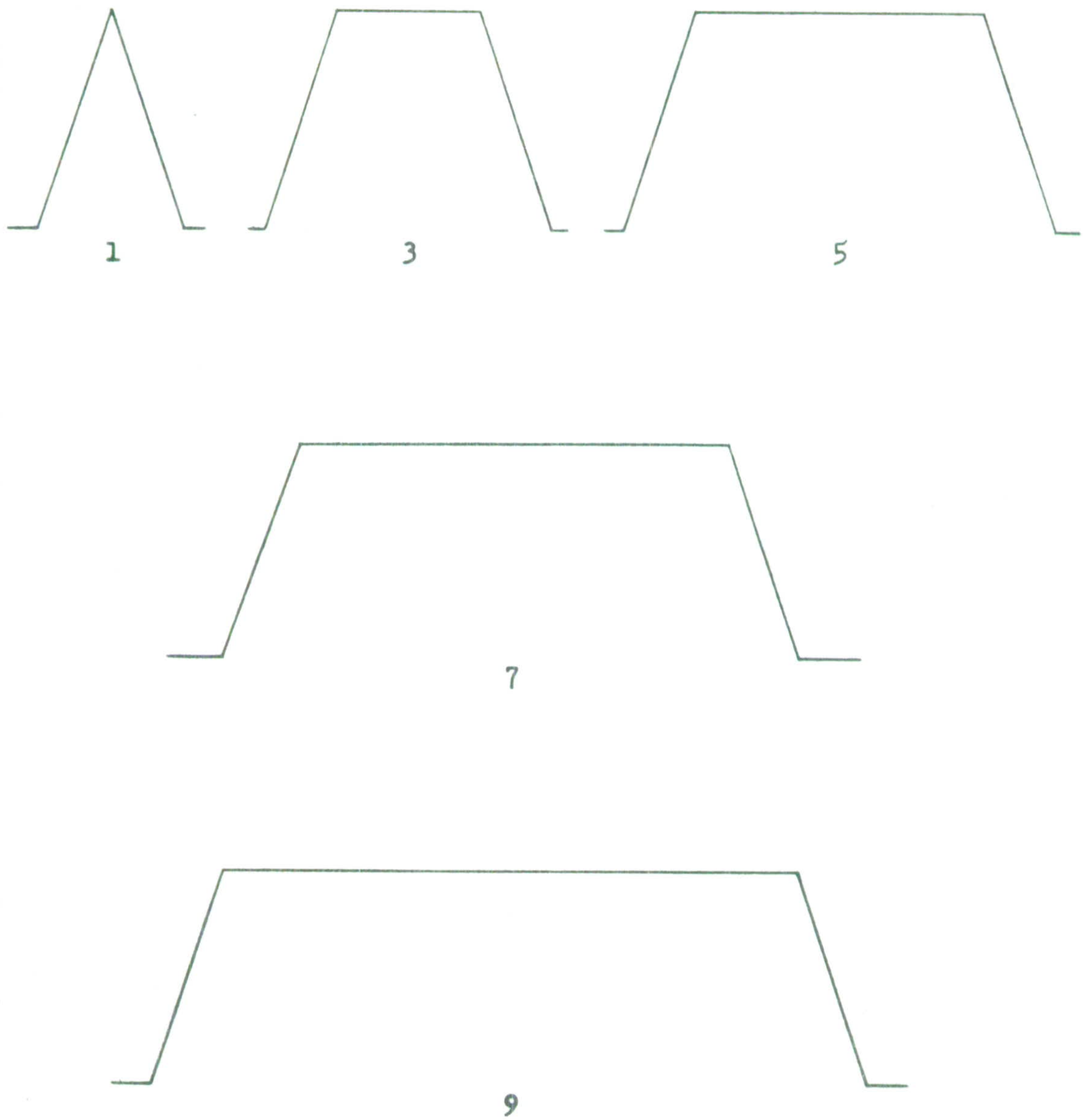

Figure 3. Representative filter response curves.

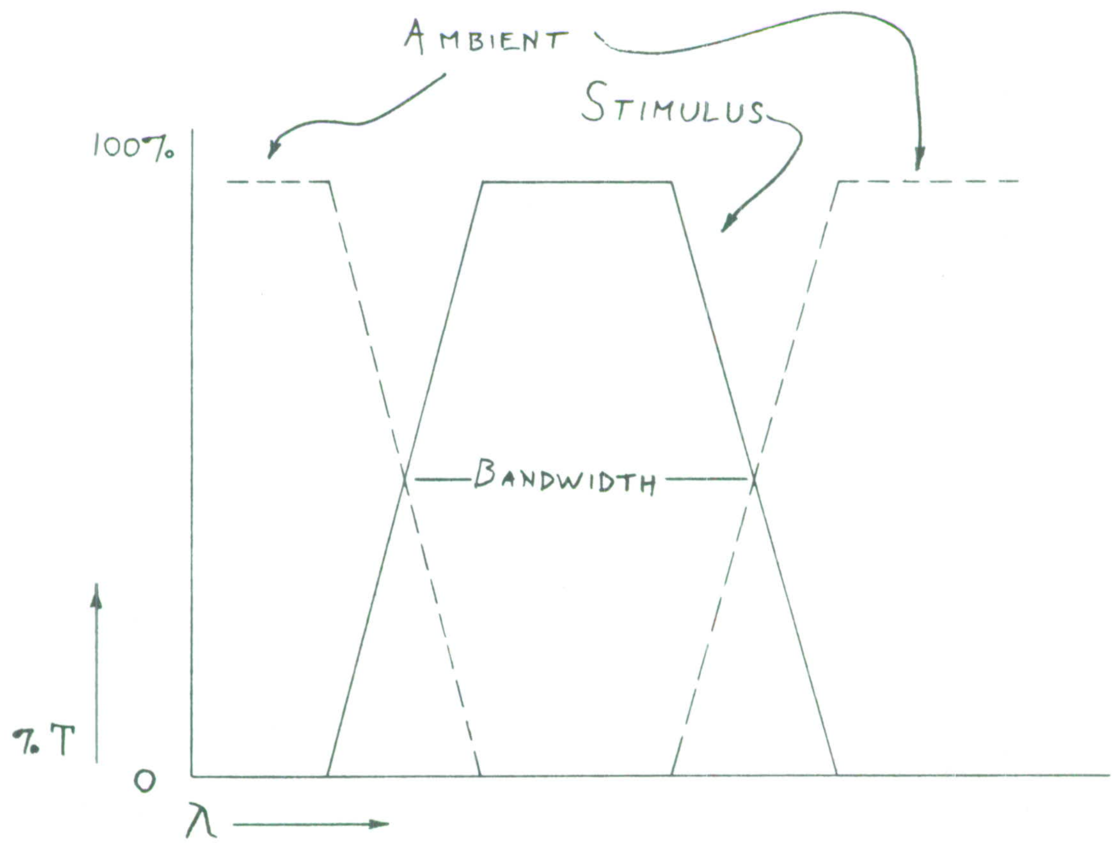

Figure 4. Same bandwidth for ambient and stimulus.

be the same, and similarly in all "+" cases, where the transmittances of the filters clearly overlap, it is desirable to avoid contamination in all "-" instances. In order to meet this condition, it follows that the top of the next largest filter response graph must be no wider than the base of the present one, with the result that the bandwidth of each succeeding filter combination must be greater than that of its predecessor by at least twice the length of the cut. For a cut of 20 mμ, the respective bandwidths for Cases 1, 3, 5, 7, and 9 of Table V are then 20 mμ, 60 mμ, 100 mμ, 140 mμ, and 180 mμ. Since the entire set of dichroic filters extends from 460 mμ cut to 640 mμ cut, a range of 180 mμ, it follows that, given the conditions imposed above and by the experimental design, there can be only one spectral replication of this experiment as presently conceived, and that it must be centered about a wavelength of 550 mμ.

The spectral response for each ambient and stimulus condition is synthesized from dichroic filter pairs in the following manner. For the ambient, light is transmitted in parallel through a short-cutting short-wavelength-pass filter and a long-cutting long-wavelength-pass filter, resulting in suppression of the central wavelengths, where neither filter transmits. For the stimulus, light is transmitted in series through a long-cutting long-wavelength-pass filter and a short-cutting short-wavelength-pass filter whose spectral transmittance curves overlap in the desired band, resulting in transmission of only those wavelengths where both filters transmit. Specific filter sets used for the different ambient and stimulus spectra are listed in Table VI; their spectral transmission curves are reproduced in Figure 5.

In order to compare subjective intensification of the stimulus image over different ambient spectra, including white light, it was necessary first to equate the brightness of each colored ambient to that of a standard white for each subject. This was accomplished by providing a means for the Experimenter to switch abruptly from each colored ambient to the standard white and back at the Subject's command and by allowing the Subject to adjust the brightness of the colored ambient to match that of the white standard. Twelve determinations were made for each of the five colored ambients, and the mean colored-white balance was recorded for each Subject and used subsequently for his individual stimulus threshold measurement. Treatments were balanced for the effects of novelty and learning both overall and within component sessions, using a Latin square technique. The ambient matching phase took about one hour, and the stimulus threshold phase took about two and one-half hours, divided into three sessions by ten-minute rest periods. A ten-minute dark-adaptation period was provided before each run, although evidence indicates that most observers adapt to light intensities used in this experiment in one minute or less[10]. The twelve subjects, professional and technical employees of Hughes Aircraft Company, were screened for color vision anomalies with the Ishihara charts.

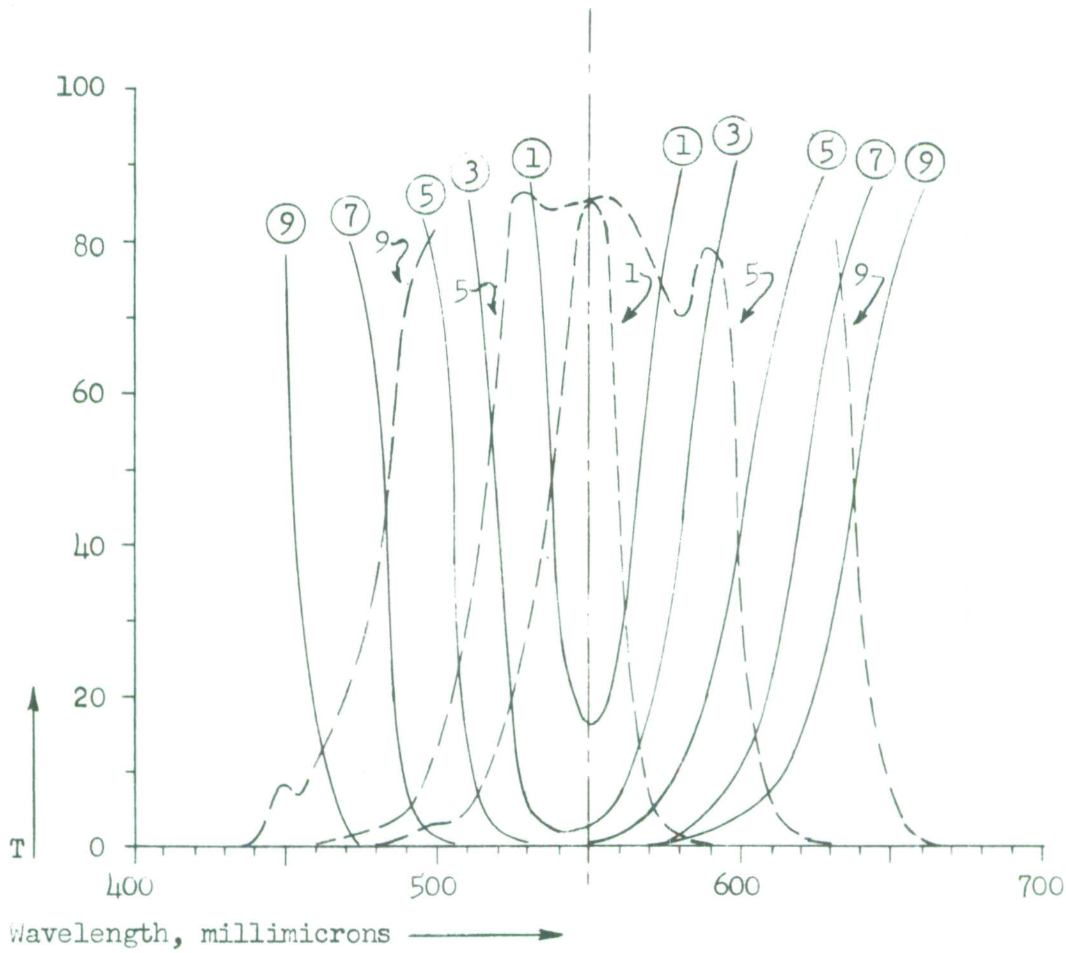

Figure 5. Measured stimulus and ambient response curves. (Intermediate stimulus curves are omitted for clarity.)

Table VI. Filter Specifications

Central Wavelength: 550 mμ

Bandwidth	Stimulus Short Filter	Stimulus Long Filter	Ambient Short Filter	Ambient Long Filter
1: 20 mμ	540	560	560	540
3: 60 mμ	520	580	580	520
5: 100 mμ	500	600	600	500
7: 140 mμ	480	620	620	480
9: 180 mμ	460	640	640	460

The method of adjustment[9] was used for both phases of the experiment by providing subjects with start-stop-reverse control of a motor-driven polarizing disc, and asking them to match the intensity of the colored ambient (which was adjustable) to that of the standard white, requesting the Experimenter to switch from the one to the other as many times as they considered necessary, for the ambient-matching phase of the experiment. For the stimulus threshold determination phase, the subjects were instructed to adjust the intensity of the checkerboard stimulus image until it was "just barely visible" on the given ambient background. Le Grand[16] points out the possible dependence of such data on non-linearities of the control mechanism; consequently, auxiliary neutral density filters were employed in series with the adjustable polarizer-analyzer combination to assure operation of the latter in the most linear portion of its density characteristic. The laboratory installation is described in greater detail in the next section; and the exact treatment sequence, as well as verbal instructions given to the subjects, are reproduced in Appendix II.

IV. LABORATORY IMPLEMENTATION

The laboratory installation for the Shared Spectrum experiment was required to provide the following functions:

- Additive synthesis of the spectral characteristics of the ambient field.
- Subtractive synthesis of the spectral characteristics of the stimulus image.
- For the matching phase of the experiment, quick change from colored to white field and *vice versa*.

- Control by the Subject of (a) brightness of the colored field for the matching phase, and (b) brightness of the stimulus image for the threshold determination phase.

- Provision for the use of fixed neutral density filters to set stimulus and ambient brightness ranges in accordance with the results of pretests.

Experimental Area

The study was conducted in adjacent rooms, with a rear projection screen placed at seated eye level in the connecting doorway. Figures 6 and 7 show plan and section views of the laboratory. Except for the twenty-by-twenty-inch (51 cm.) square of high-grade drafting vellum which comprised the screen, the entire doorway was sealed with construction board. The ambient background and the stimulus image were projected to the screen from separate off-axis projectors over a distance of thirteen feet (3.9 m.), with a floor-to-ceiling mask located directly in front of the projectors to minimize stray light at the screen. The Subject was seated with his head free and his eyes approximately fifty-five inches from the screen.

Stimulus

The stimulus image consisted of a twenty-five square checkerboard, six inches (15 cm.) along each side, of which the central square was light. It was projected additively to the ambient field, which covered the entire screen. Because film with an image density of greater than 3.0 was used in preparation of the stimulus slide, the dark squares of the checkerboard may be considered to contain only light of the ambient spectral distribution. Visual angles subtended from the vantage point of the Subject were twenty-one degrees for the entire ambient field, six degrees for the stimulus checkerboard, and one degree for an individual checkerboard square.

The means of synthesizing the desired spectral characteristics of the stimulus beam is shown in Figure 8. Slots were provided in a filter assembly for fixed neutral density filters, a long-pass dichroic filter, a short-pass dichroic filter, and a stationary Polaroid analyzer, all in series with the projector beam. The device was situated as close as possible to a rotatable polarizing disc and the projector lens, to minimize loss of light and vignetting due to the effective exit pupil of the filter assembly. (Contrary to the schematic representation of Figure 8, filter slots were carefully wedged, to prevent the possibility of near-parallel glass surfaces generating secondary images at the screen.)

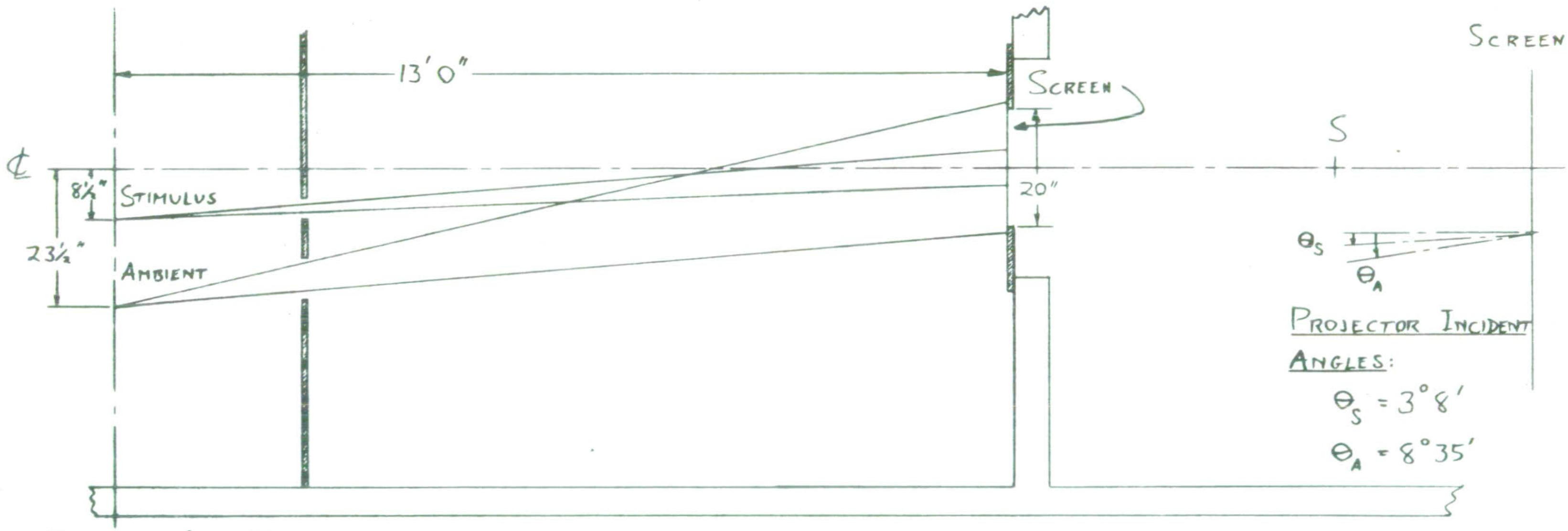

Figure 6. Plan view of experimental area.

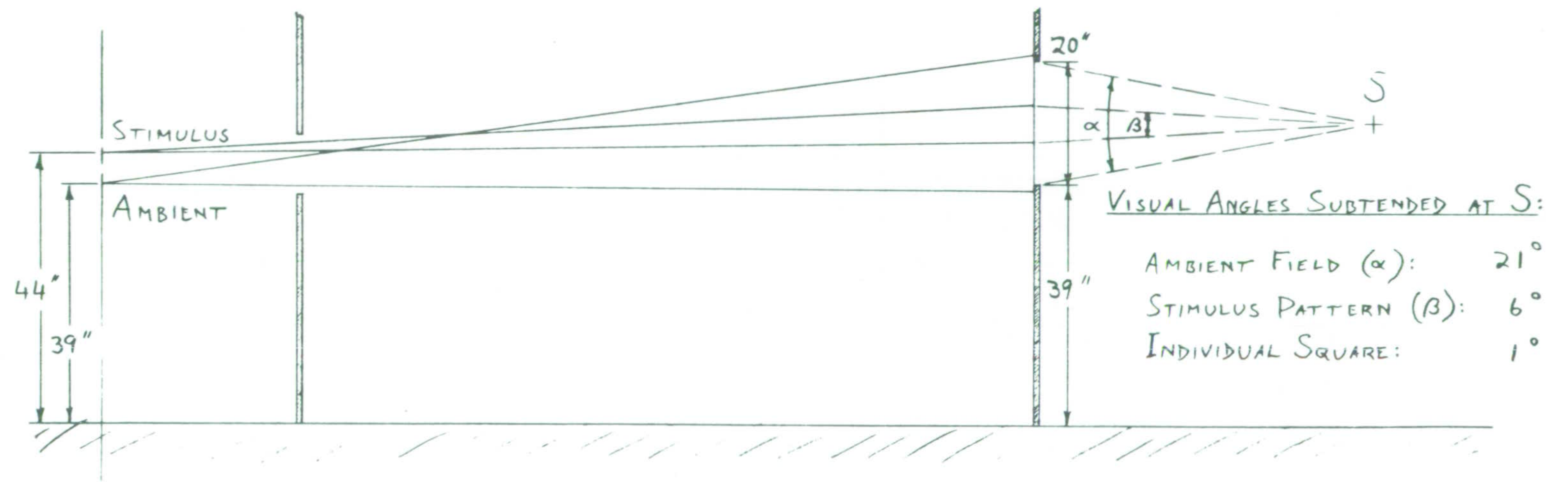

Figure 7. Section through ℄.

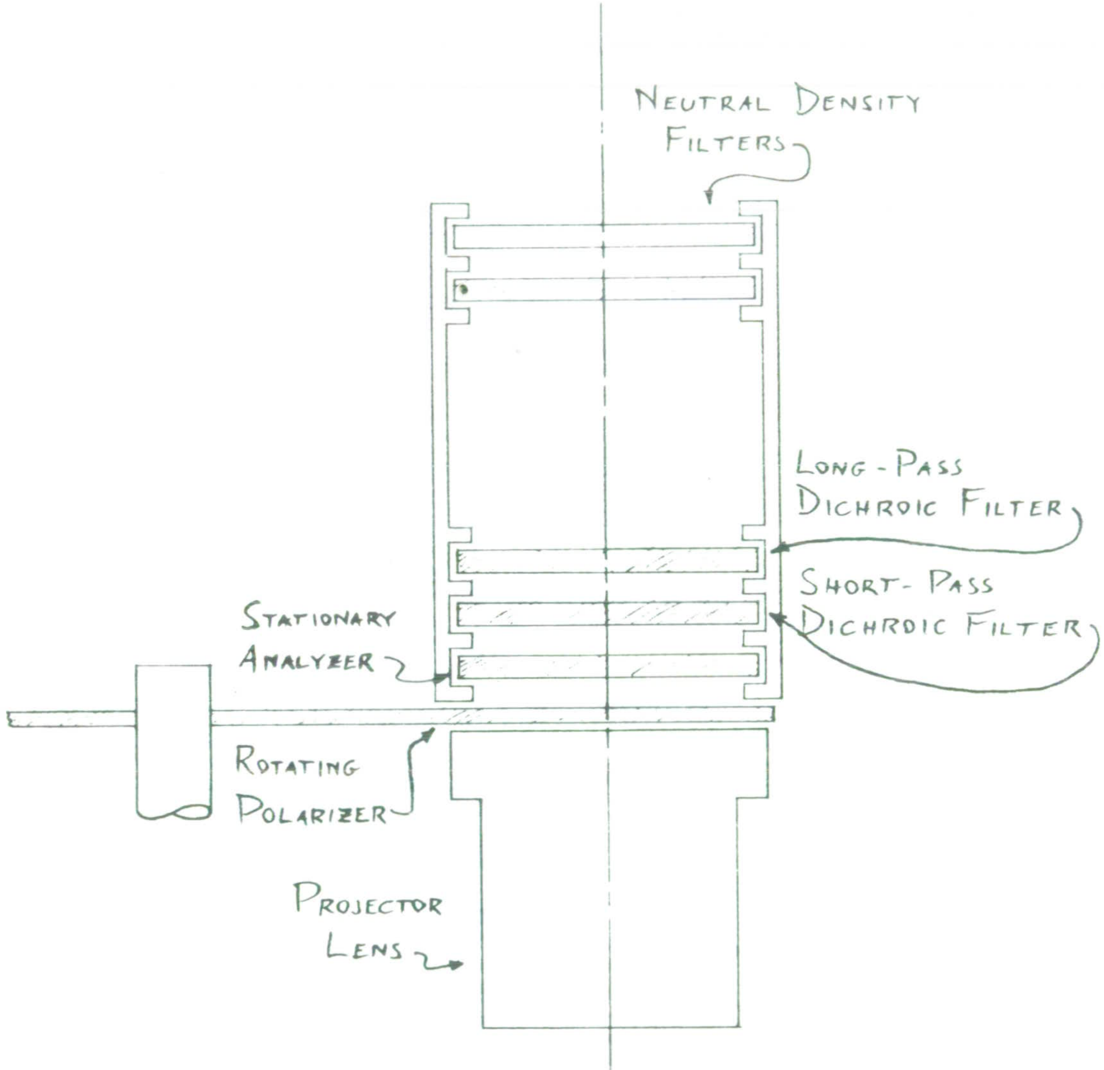

FIGURE 8. STIMULUS FILTER HOLDER.

Ambient Field

The ambient filter assembly, shown in Figure 9, was constructed to slide, with stops permitting it to be shifted manually between the white and colored positions. This device actually comprised two filter holders side by side, only one of which could be centered in the projector beam at one time. Because the polarizing disc did not move laterally, and only the colored side contained an analyzer, the brightness of the white beam was independent of the rotatable disc; hence, the brightness of the colored ambient field could be changed at will without affecting the white reference field.

Additive synthesis of the colored ambient field was accomplished by dividing the projector beam with a partially aluminized beamplitter, placing the short-pass dichroic filter in the reflected beam and the long-pass dichroic filter in the transmitted beam, and collimating the two with a fully aluminized mirror. A 0.4 neutral density filter was employed in the transmitted beam to compensate for a corresponding difference in transmittance between the two optical paths. Edge masking obviated the need for precise beam convergence at the screen. Both the stimulus and the ambient field optical assemblies were constructed from heavy illustration board, sprayed flat black to minimize scattering, and mounted on a single optical bench placed crosswise in front of the respective projectors.

Brightness Control

Variation of field or image brightness was effected by the rotatable polarizing disc alluded to above. Driven by a 0.1 r.p.m. synchronous motor, the disc could be energized by either the Subject, in making his adjustments, or by the Experimenter, in following his offset schedule, but not by both simultaneously. Figure 10 shows the switching circuit which controlled the motor; electrical braking reduced overshoot to an imperceptible amount. A scale of density units was mounted directly on the disc, so that no mechanical linkage was involved in making readings. A reference line was mounted coplanar with the scale to minimize parallax.

Experimenter control of the polarizer took the form of "Brighter" and "Darker" pushbuttons mounted at the top of the clipboard used for transcribing data, and a cardboard "shutter" to interrupt the beam during adjustments. The Subject was provided with a small control panel containing a single lever-actuated spring-return switch. Movement of the switch to the right brightened the image, and *vice versa*.

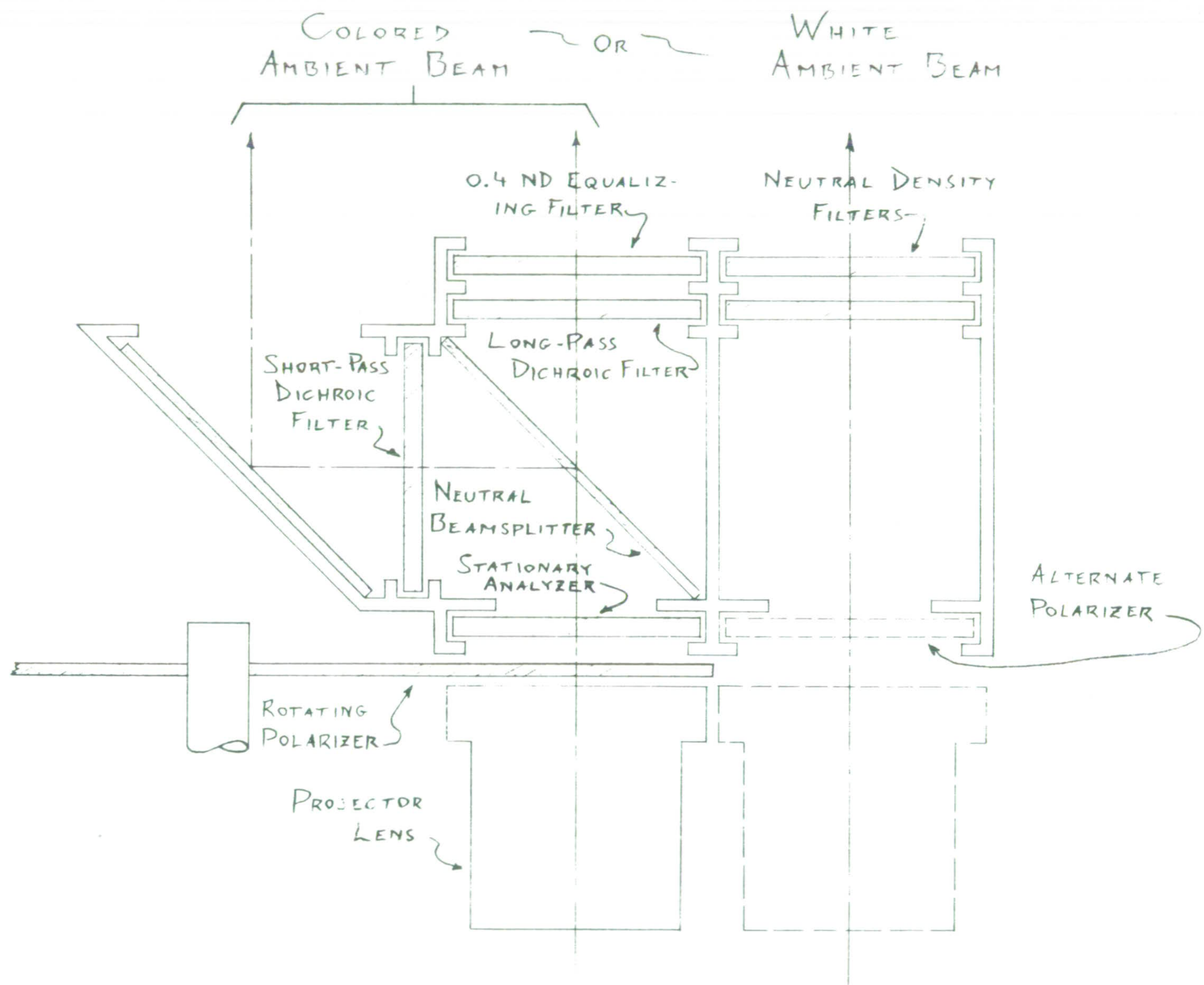

FIGURE 9. AMBIENT BEAMSPLITTER AND FILTER HOLDER.

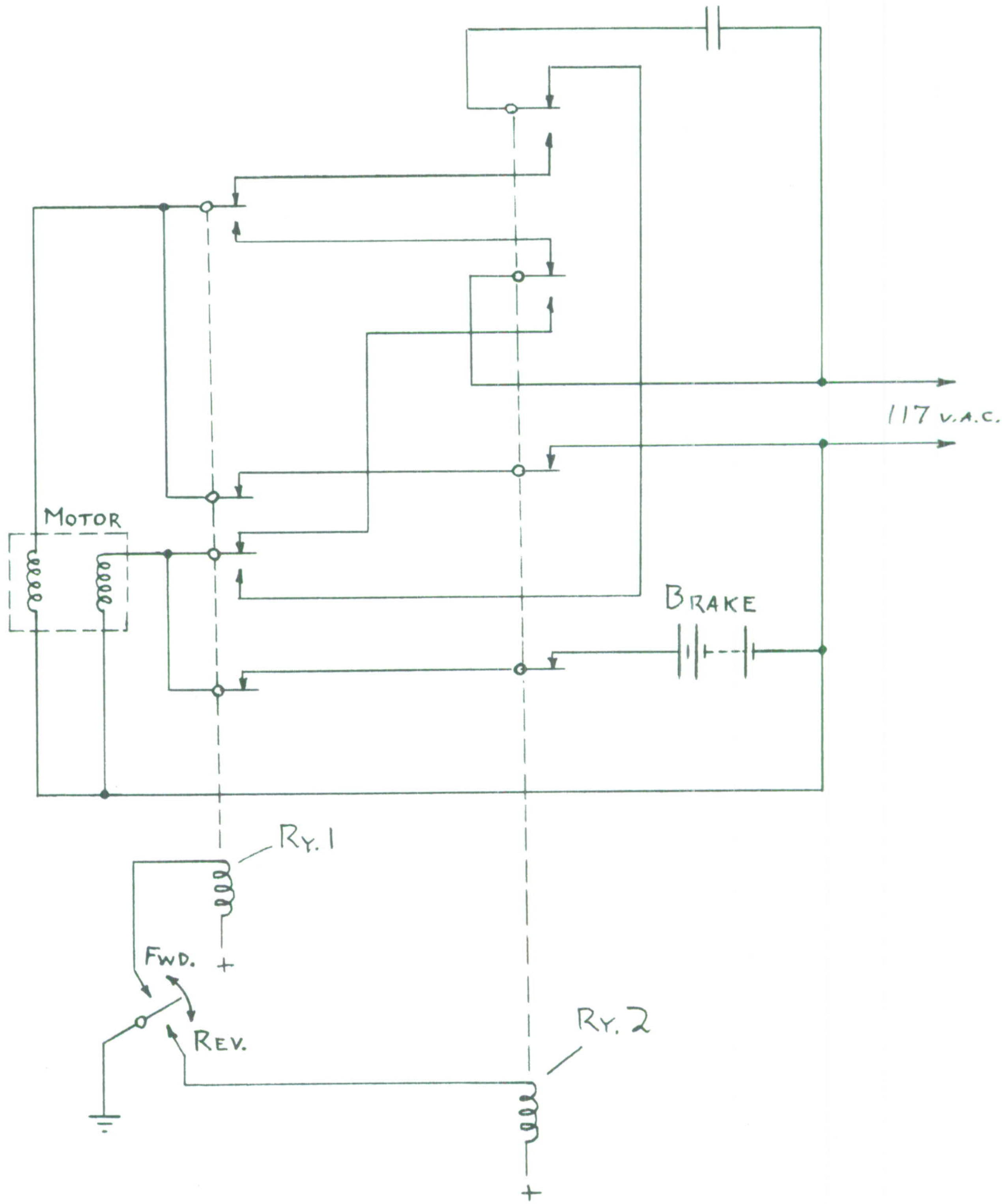

Figure 10. Polarizing disc motor control circuit.

Because the motor-operated polarizing disc was mounted permanently on the right projector, it was not possible to provide Subject control of the other machine. Consequently, the first (ambient matching) phase of the experiment was conducted with the ambient assembly at this projector; for the second phase, the stimulus filter holder was placed in front of the right projector and the ambient was moved to the left. In the latter mode, the single polaroid disc was replaced in the white beam with a two-by-two-inch square of polaroid material, shown as the "alternate polarizer" in Figure 9; polarization of the beam is incidental at this point, as the device is intended only to provide absorption equivalent to that of the polaroid disc. Equalization of the colored beam to the white according to the individual Subject's previous match was accomplished with a separate polarizer-analyzer disc combination, pinned at the center so that they could rotate with respect to one another, and provided with a scale similar to that ot the motor-driven device.

The means used for calibration of all laboratory equipment, before, during, and after all runs, are fully described in Appendix III.

Units

In view of the well-known Weber-Fechner relationships, it is reasonable to expect the data accruing from this experiment to follow a logarithmic distribution. Previous investigators, regardless of whether or not a statistical evaluation was performed, have recorded both threshold and brightness match studies in terms of "relative log units." There is, however, no standard logarithmic unit of light intensity.

At the cost of compounding further the already diverse array of optical units, we propose to quantify the phrase, "relative log units," by employing a specific unit, and by relating it to a constant, similarly to the manner in which sound pressure level is referred to a recognized standard (e.g., decibels referred to 0.0002 microbar). Because it is logarithmic, and because its use simplifies calculations involving filters calibrated similarly, we have selected the unit of optical density, δ_λ, which is defined as the logarithm of the ratio of unattenuated light energy to light energy transmitted through a given medium, as a function of wavelength. In most cases, optical density is considered to be the integral of δ_λ over the visible spectrum; and hence the subscript is omitted.

In order that our laboratory data shall be non-negative, the standard value of brightness to which our density values will relate must be greater than any we expect to encounter; and we have consequently chosen 100 footlamberts as our standard brightness. We therefore define a new unit of brightness, specific optical density, δ_s, as the logarithm to the base ten of the ratio of 100 footlamberts to the measured brightness, in footlamberts:

$$\delta_s = \log_{10} (100 \text{ footlamberts/measured brightness})$$

As an example, suppose that open-gate screen brightness has been measured as 39.8 footlamberts, yielding

$$\delta_s = \log_{10} (100/39.8) = \log_{10} 2.51 = \underline{0.40}.$$

If a filter having a density of 1.80 is now placed in the projector beam, the resultant specific optical density of the screen is simply the sum of the two:

$$\delta_{s_1} = 0.40 + 1.80 = 2.20$$

Similarly, if the above combination is used for an experimental run, and the Subject indicates a match with an additional polarizer density of 0.82, the specific density of the screen corresponding to the match is:

$$\delta_{s_m} = 0.40 + 1.80 + 0.82 = 3.02$$

The experimental data was recorded in exactly that fashion. Units of specific optical density have an exact meaning, are already in logarithmic form, and are compatible with the calibrations of all laboratory equipment except the Macbeth Illuminometer, the readings from which were easily converted in the above manner.

It is of some interest to examine the means by which these data may be translated into terms used by other investigators. "Relative log units," of course, we already have. To consider differences in threshold brightnesses in decibels (e.g., Williams and Hanes[24]), multiply density values by ten. To compute the Fechner Fraction (relative luminance threshold), $\Delta B/B$, where, as in our case, the stimulus image is added to the background light already present on the screen, $B/S = \log^{-1} (\delta_{s_2} - \delta_{s_1})$, where δ_{s_1} is the specific optical density of the stimulus image, and δ_{s_2} is the specific optical density of the ambient background, both measured at the screen. The discrimination index, of course, is the inverse of

the Fechner Fraction, and hence is equal to $\log^{-1}(\delta_{s_1} - \delta_{s_2})$. Finally, specific optical density may be converted into conventional linear brightness units by the following:

$$B_{footlamberts} = \log^{-1}(2.00 - \delta_s)$$

$$B_{millilamberts} = \log^{-1}(1.97 - \delta_s)$$

V. RESULTS

Mean specific optical densities for subjective matching of the five ambient spectra to the standard white are shown in Table VII and Figure 11. The mean square deviation within observers was only 0.0028 density units, compared to a mean square deviation between observers of 0.208 density units; we were thus able to conclude that the individual ambient densities used for the threshold phase of the study represented dependable judgments of equivalence to the standard white. Values of specific optical density decreasing with increasing width of the ambient rejection notch (corresponding to a logarithmic increase in projector beam intensity) are to be expected, since removal of wavelengths from the visible spectrum clearly requires that the amplitude of the remaining light be augmented, if the total energy is to remain unchanged. The effect is amplified by the fact that, as illustrated by the form of the photopic luminosity function, the observer is most sensitive to those wavelengths which we have suppressed. The analysis of variance is given in Appendix IV.

As noted above, the experimental design for the stimulus threshold phase of the study provides for analysis of results in terms of (1) thresholds for ambients 3, 5, 7, and white with stimuli 3, 5, and 7, referred to as the central subset; (2) thresholds for relational parameters -2, 0, and +2 with stimuli 3, 5, and 7; and (3) thresholds for relational parameters -2, 0, and +2 with ambients 3, 5, and 7.

Thresholds comprising the central subset are shown in Table VIII and Figure 12. The analysis of variance, reproduced in Appendix V, shows significance at the 0.005 level of probability for stimuli, ambients, subjects, and the ambient-subject interaction. Duncan's Multiple Range Test[5] shows ambient 7 to be significantly higher in specific optical density (and hence in luminous sensitivity for all stimulus spectra; that is, thresholds were lower under this ambient) than ambients 3 and 5 at the 0.01 level, and higher than white at the 0.05 level. With means which do not differ significantly from one another at the latter probability of error enclosed in parentheses, the ambients rank as follows, beginning with the highest density (i.e., the lowest threshold): A7 (White, A5) A3.

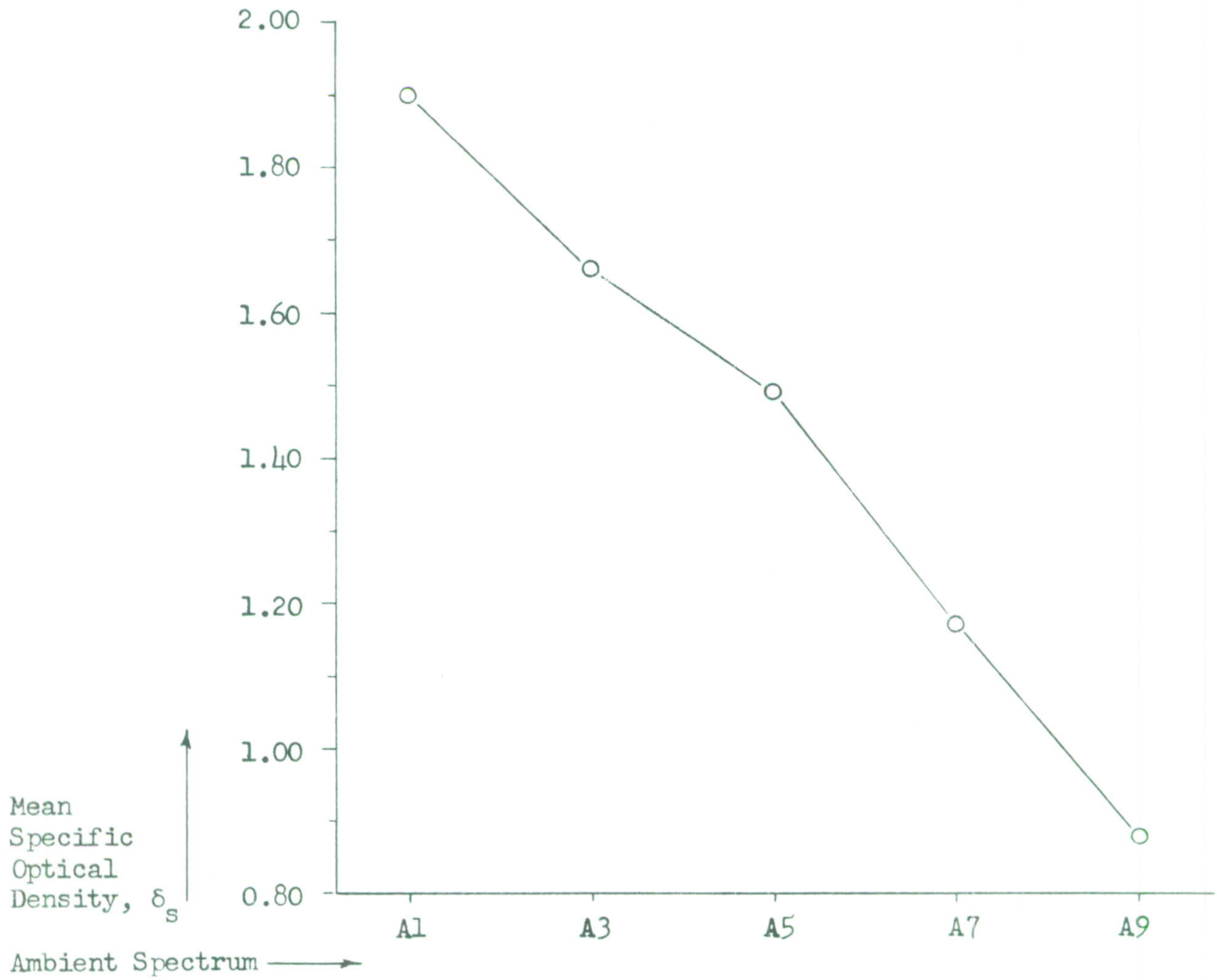

Figure 11. Mean specific optical densities for the five ambient spectra.

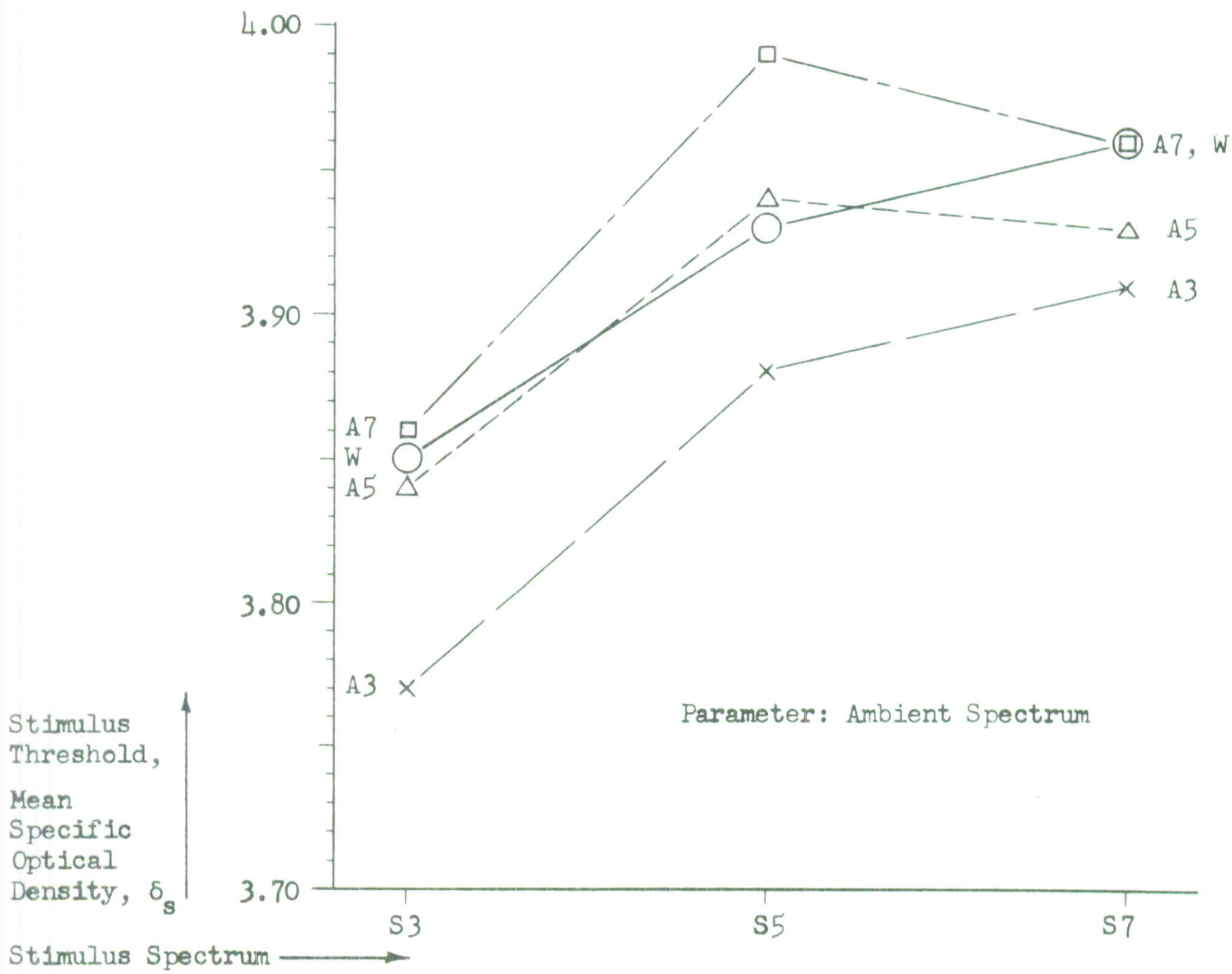

Figure 12. Stimulus thresholds for central subset.

Table VII. Mean Colored-White Ambient Matches Across Subjects

Subject:	1	2	3	4	5	6	7	8	9	10	11	12	Ambient Means
Ambient													
A1:	1.91	1.92	1.86	1.92	1.94	1.87	1.89	1.91	1.88	1.86	1.86	1.97	1.90
A3:	1.74	1.76	1.68	1.71	1.63	1.72	1.77	1.75	1.72	1.40	1.59	1.50	1.66
A5:	1.49	1.51	1.44	1.52	1.57	1.46	1.54	1.54	1.49	1.40	1.41	1.46	1.49
A7:	1.18	1.16	1.10	1.23	1.18	1.13	1.24	1.20	1.19	1.12	0.98	1.28	1.17
A9:	0.88	0.89	0.77	0.89	0.77	0.81	1.14	0.92	1.03	0.76	0.83	0.84	0.88
Subject Means:	1.44	1.47	1.37	1.46	1.42	1.40	1.52	1.46	1.46	1.31	1.33	1.41	

Units: Specific optical density, without colored filters in place.

Table VIII. Stimulus Thresholds for the Central Subset

Ambient:	A3	A5	A7	White	Stimulus Means
Stimulus					
S3:	3.77	3.84	3.86	3.85	3.82
S5:	3.88	3.94	3.99	3.93	3.93
S7:	3.91	3.93	3.96	3.96	3.94
Ambient Means:	3.85	3.90	3.94	3.91	

Duncan's Test was also performed with the means recorded for ambients in combination with individual stimuli. With fewer degrees of freedom, they are not as easily separable; nevertheless, with 0.05 probability of error, they can be grouped as follows, beginning with the highest. The order in all cases is that which obtained in the study, even though differences in means did not attain significance:

S3: (A7, W, A5) A3

S5: (A7, A5) (A5, W) (W, A3)

S7: (A7, W, A5, A3)

Arrangement of the data in terms of the relational parameters -2, 0, and +2 is shown in Tables IX and X and Figures 13 and 14. In order to tabulate these responses in meaningful form, it is necessary to subtract from each mean threshold the threshold obtained for the same stimulus with white ambient, since different stimuli and different ambients are grouped together under the same relational parameters. The entries in the table, and the ordinates in the graph, therefore represent the difference between specific optical density at threshold for the given stimulus-ambient combination and specific optical density for the same stimulus with white light. Points above the zero axis of Figures 13 and 14 show an advantage over white ambient, and *vice versa*.

Table IX. Relational Parameters versus Stimuli

Relative Bandwidth:	-2	0	+2
Stimulus			
S3:	-0.01	-0.08	-0.06
S5:	0.06	0.01	-0.05
S7:	0.02	0.00	-0.03

Table X. Relational Parameters versus Ambients

Relative Bandwidth:	-2	0	+2
Ambient			
A3:	-0.07	-0.08	-0.05
A5:	-0.01	0.01	-0.03
A7:	0.06	0.00	0.00

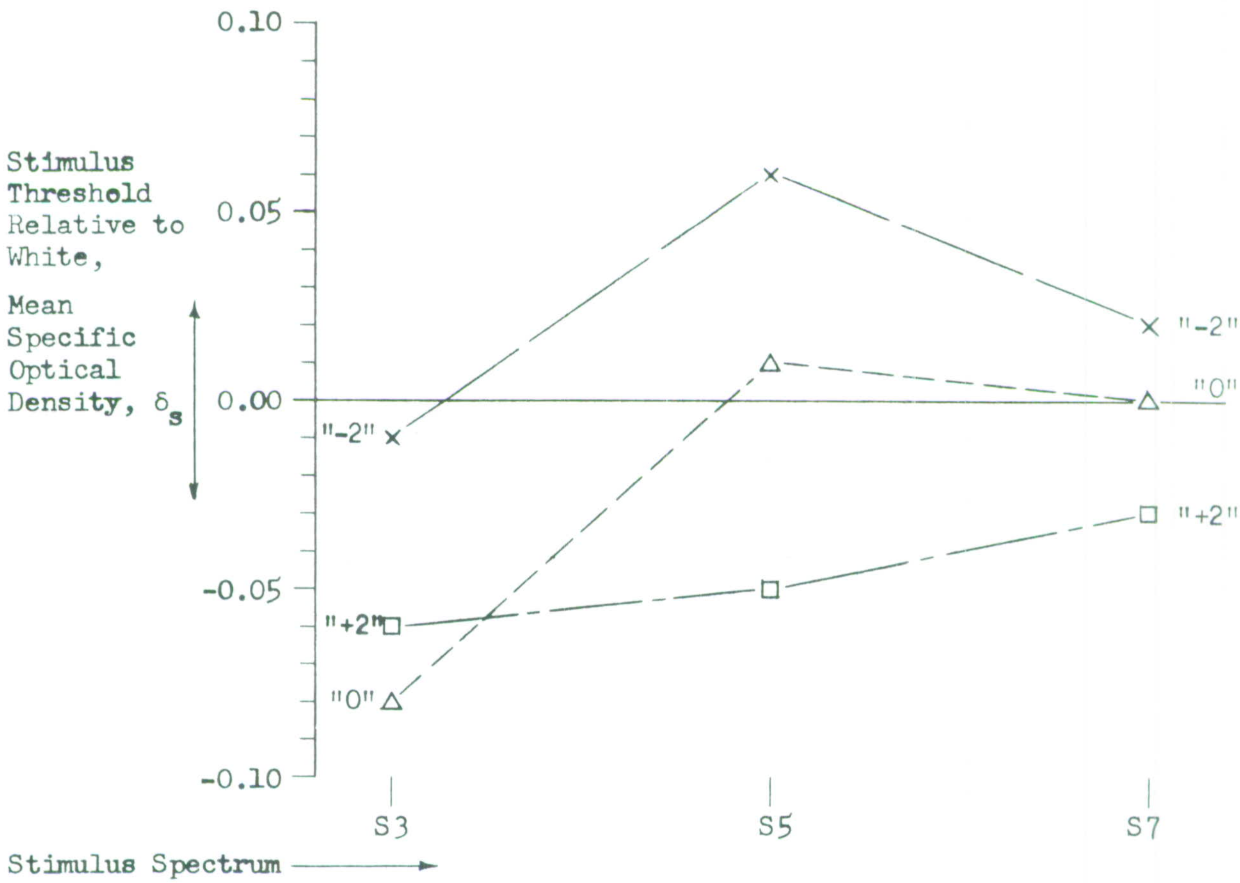

Figure 13. Relational parameters versus stimuli.

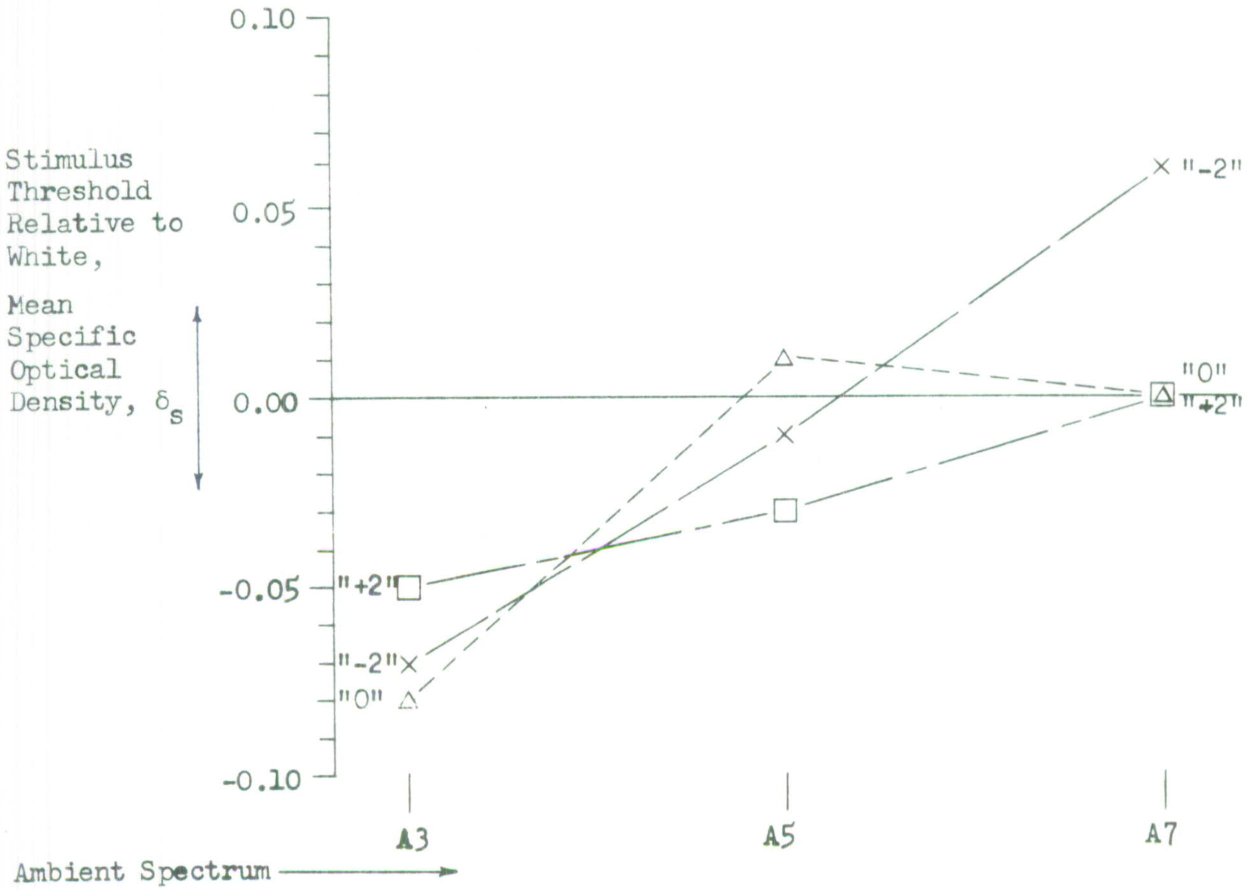

Figure 14. Relational parameters versus ambients.

VI. ANALYSIS

Although ambient 7 is clearly superior to the other ambients, including white, for all stimulus spectra, the differences in threshold sensitivity were not as great as had been expected; the largest difference, which obtained for the case of stimulus 5 and ambient 7, was only 0.06 density units, equivalent to 0.6 db. increase in detectability over the same stimulus under white light. Also surprising was the fact that so many of the ambient-stimulus combinations were inferior to the same stimulus under white light. Ambient 3 averaged 0.05 density units lower than white, with the lowest treatment -- S3-A3 -- being 0.08 lower. Arranging the data in terms of relational parameters failed to elicit much information: although there is a clear trend for the -2 case (stimulus bandwidth less than ambient bandwidth) to show a lower detection threshold than either 0 or +2 when relational parameters are plotted against stimulus bandwidths, the trend breaks down entirely when the data is plotted against ambient bandwidths. It would appear that visual enhancement is not independent of the bandwidth of either the stimulus or the ambient.

Since one of the questions posed at the outset was the ability of the observer to adapt to colors of low saturation, it is interesting to examine the different ambient spectra from the standpoint of colorimetric hue and saturation (purity). If the stimulus spectral response curves were synthesized from filters which transmitted only and completely within the designated spectral band, then dominant wavelength would vary with stimulus bandwidth as shown in Figure 15; chromaticity coordinates were calculated by the weighted-ordinate method, and hue and saturation determined graphically from a standard C.I.E. chromaticity diagram. As bandwidth increases from zero, dominant wavelength moves toward the yellow, reaching 574 mμ at a bandwidth of 210 mμ centered about 550 mμ. At the same time, excitation purity[2] diminishes, as shown in Figure 16, from 1.0 to 0.2 at the 210 mμ bandwidth. These two functions are combined in Figure 17, which shows the locus of increasing bandwidth on a graph of dominant wavelength versus purity. The actual locations of Stimuli Nos. 1, 3, 5, and 7 are shown for reference; Number 9 is off to the right at λ_D = 584 mμ, p_e = .06.

The dashed line represents the same locus for the ambient function in terms of complementary dominant wavelength and purity. It will be noted that Ambients Nos. 5 and 7 are closely complementary to Stimuli Nos. 3 and 5, respectively; recall that the Stimulus 5 - Ambient 7 combination ranked highest in the experimental data, while Stimulus 3 - Ambient 5 was grouped with the lowest!

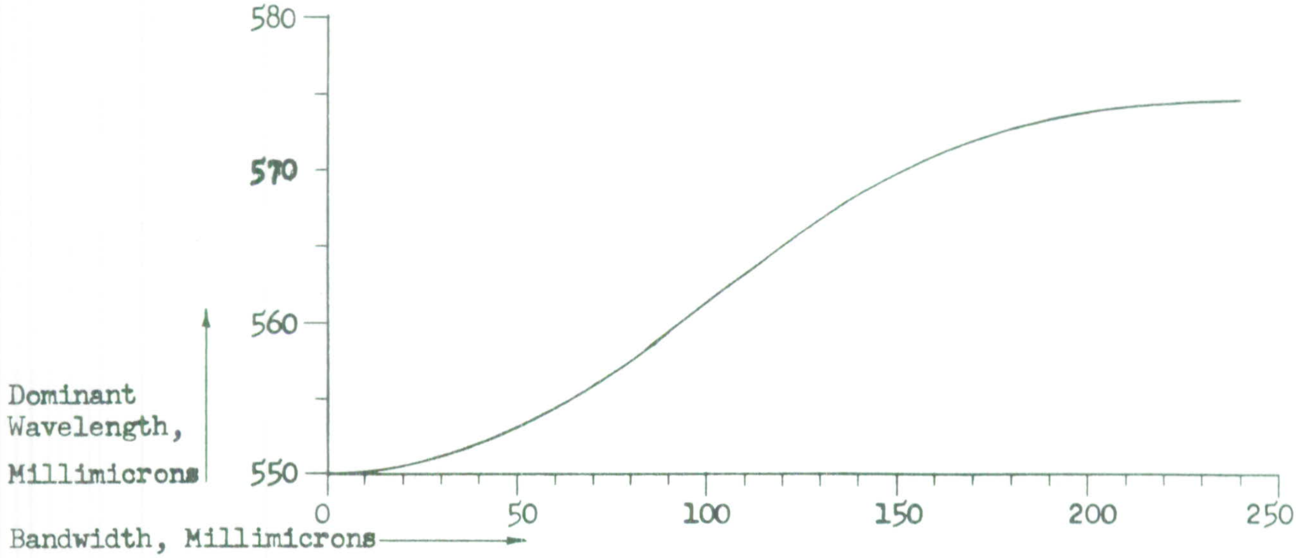

Figure 15. Dominant wavelength as a function of bandwidth.

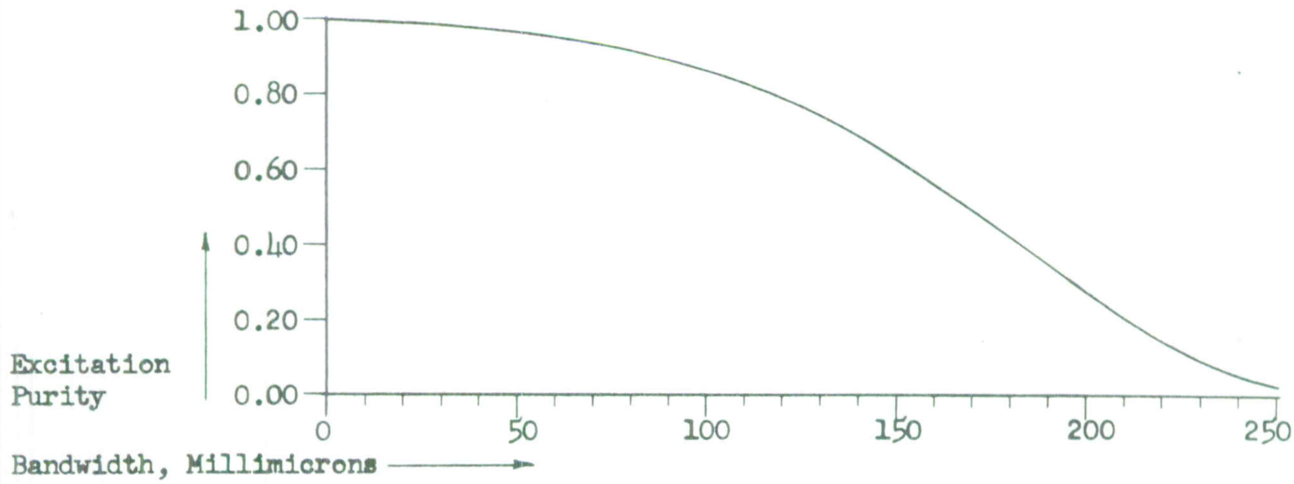

Figure 16. Purity as a function of bandwidth.

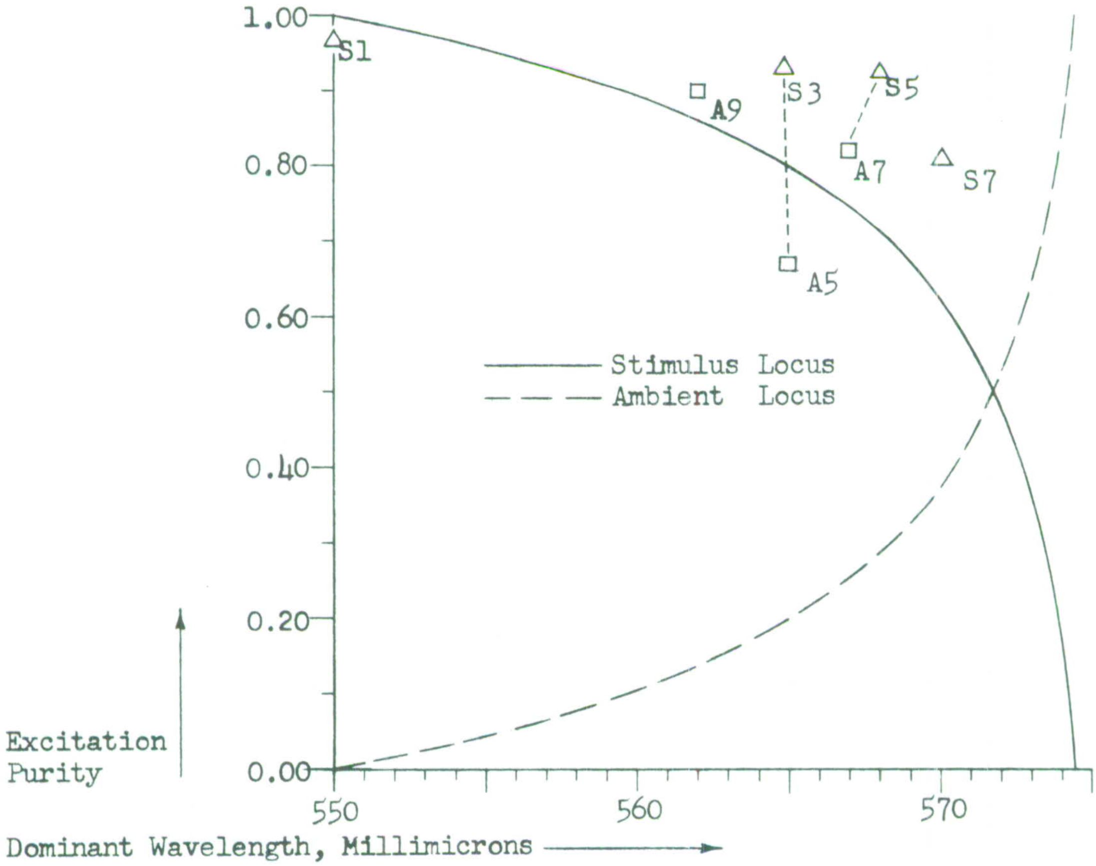

Figure 17. Dominant wavelength versus purity.

Hence, there is no demonstrable relationship between complementariness and stimulus threshold in the present data.

In order to determine whether or not the threshold measurements could have been predicted on the basis of the Wald[23] results, a weighting function was computed from the data presented in Figure 7 of the referenced paper. It was reasoned that the luminous sensitivity of the observer to any stimulus-ambient combination should relate closely to the degree with which the receptors responding to the ambient spectrum were stimulated by the ambient and not by the stimulus, and to the degree with which the receptors responding to the stimulus spectrum were stimulated by the stimulus and not by the ambient; hence, the function

$$f(\lambda) = \int_{400}^{700} \Big[A(\lambda) - S(\lambda)\Big]\Big[\ R(\lambda) + B(\lambda) - G(\lambda)\Big]\ d\lambda$$

where

$A(\lambda)$ = ambient illumination spectrum

$S(\lambda)$ = stimulus image spectrum

$R(\lambda)$ = the action spectrum of the red receptor

$G(\lambda)$ = the action spectrum of the green receptor

$B(\lambda)$ = the action spectrum of the blue receptor

The weighting function comprises the portion of the above equation enclosed in the right-hand set of brackets, and is tabulated at twenty-millimicron intervals for numerical integration after multiplication (Table XI). In order that the sum of ordinates be zero for white illumination, the values of the green curve have been multiplied by the constant 1.57.

A figure of merit, $f(\lambda)$, for each stimulus and each ambient was obtained by multiplying spectral transmittance by the corresponding value of $W(\lambda)$ at 20 mμ intervals and adding. Figures for each stimulus-ambient combination were then determined by subtracting the stimulus figure from the ambient figure, the entire process comprising numerical integration of the expression given above. Values of integrals computed in this fashion are shown below in Table XII, and in scatterplot form with experimentally determined thresholds in Figure 18. The correlation $r = 0.90$ of these two sets of data is significant at the 0.001 level of probability.

Table XI. Stimulus-Ambient Weighting Function, $W(\lambda)$

λ, mμ	$W(\lambda)$
400	0.42
420	0.72
440	0.63
460	0.20
480	-0.40
500	-0.73
520	-0.88
540	-0.84
560	-0.39
580	0.11
600	0.47
620	0.42
640	0.19
660	0.06
680	0.02
700	0.00

Table XII. Weighted Integrals of Stimulus-Ambient Spectra

Ambient:	3	5	7
Stimulus			
3:	0.28	1.14	1.39
5:	1.59	2.45	2.70
7:	1.08	1.94	2.19

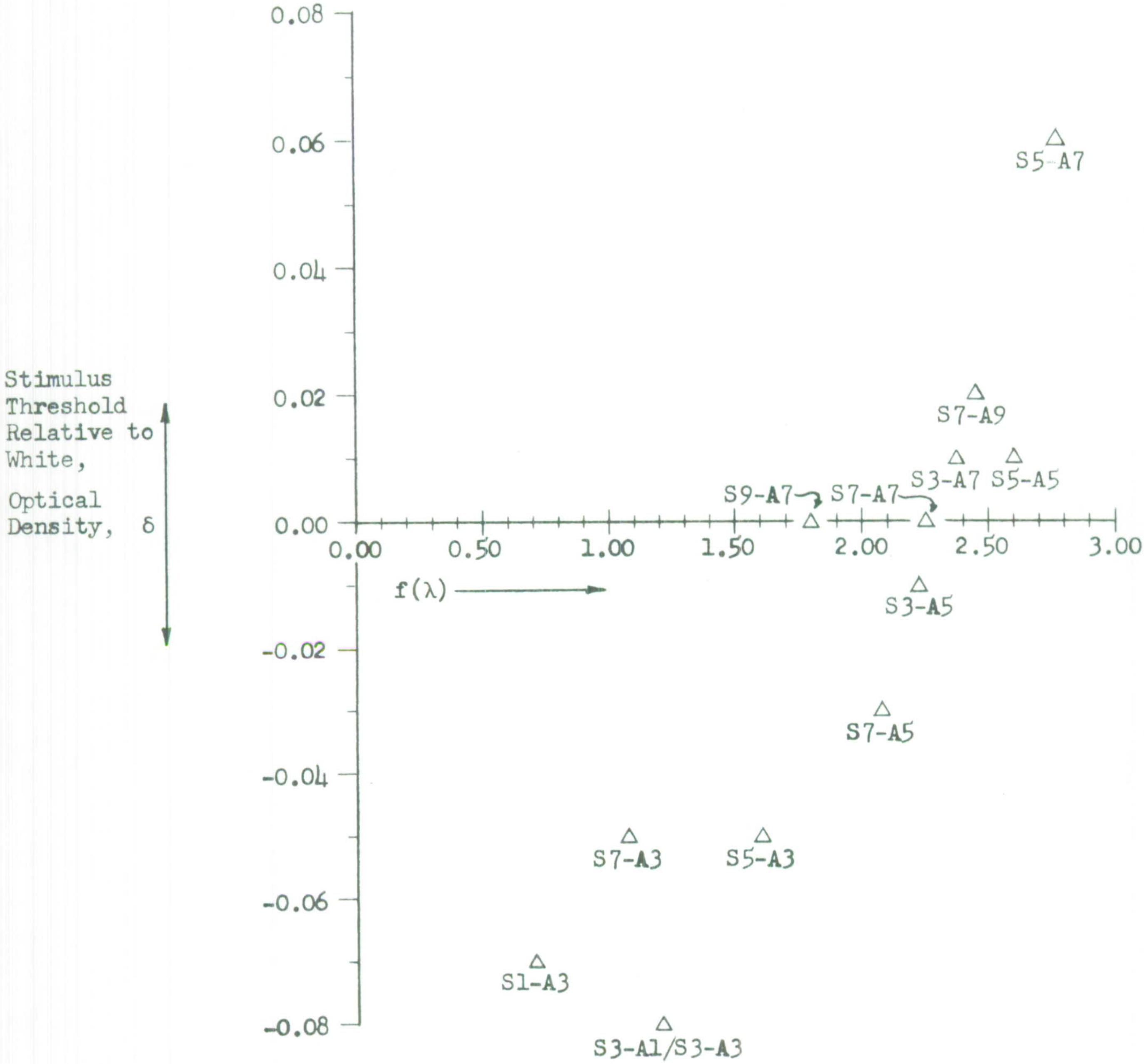

Figure 18. Scatterplot of experimental thresholds and integral functions.

In spite of this highly significant correlation, the reader must be cautioned against investing the data with unwarranted generality. The Wald results were obtained with two observers and smoothed visually; and our thresholds were measured with varying stimulus and ambient bandwidths about only one central wavelength. Furthermore, the process of multiplying the green receptor curve by a constant to obtain a zero sum for white illumination is tenuously based. Without it, the correlation becomes 0.80, however, which is still significant. We shall also beg the question of whether correlation or regression is the more appropriate technique on the grounds of paucity of data. Two conclusions, only, can be drawn at this point: barring artifacts, there is a relationship between the responses of one set of observers to the Wald two-color stimuli and the responses of another set of observers to Shared Spectrum illumination; secondly, the nature of that relationship, and particularly the question of whether the one data set can be of use in predicting the other, can only be elucidated through further study.

One of the puzzling aspects of this study is the question of why any of the stimulus detection thresholds should actually be higher with a colored ambient than with white. In the limit, as the ambient notch was narrowed, we should have expected detection thresholds to approach those obtained with white light; yet only one ambient, A7 (widest) yielded significantly lower thresholds, and A3 (the narrowest) resulted in significantly higher ones. The fact that a more intense stimulus image was required for detection with a colored ambient background than with a white background of subjectively equivalent brightness is difficult to explain and strongly suggests an artifact; what its nature may be, though, is not at all apparent at this writing. A more attractive theory might devolve upon some visual nonlinearity occurring as a function of the very much higher amplitudes (as opposed to total integrated energy) necessary to equate the wider ambient spectra to the standard white light. Replication of this experiment at other central wavelengths might prove very illuminating in this regard.

VII. CONCLUSIONS

Stimulus-ambient combinations in which the stimulus spectrum fell entirely within the ambient notch showed a clear advantage over all other combinations, with the Stimulus 5- Ambient 7 pair yielding the lowest mean thresholds. The characteristics of the available filters, together with the design of the experiment in such a way as to provide information about the relational effects of stimulus and ambient bandwidths precluded replication at central wavelengths other than 550 mμ, and it seems clear at this point

that the spectra chosen did not elicit the maximum effect; nevertheless, a statistically significant - although small - improvement in detectability was noted for Ambient 7 over that obtained with all other ambients, including white. Shared Spectrum illumination appears to be a valid technique for increasing the visibility of displays located in the missing spectral band; further experimentation should be aimed at determining those regions of the spectrum where the maximum effect is to be obtained, and at establishing general design principles by which Shared Spectrum illumination may be tailored for specific needs, such as the characteristics of a given cathode-ray tube phospor, the desire for white-appearing ambient light, etc. Correlation of future experimental results with published data on human color receptors has been suggested as a possible source for design criteria.

APPENDIX I

THE DICHROIC FILTER SET

Dichroic filters were chosen in preference to absorption filters for this experiment because of their sharpness of cut, the ability to locate the cut at any point in the spectrum, and a considerably higher attainable transmission efficiency in the blue region. In order to utilize the sharp-cutting characteristic for several replications of the basic experiment at different points in the spectrum, a corollary need was for accurate placement of each cut, so that adjacent filters could be combined as stimulus and ambient sets with minimum discrepancies in curve shape due to component filter variation.

Measurements on the received filters are shown in Tables XIII and XIV. It will be noted that defining a filter response curve between the twenty and eighty per cent points leaves room for considerable improvisation about the toe of the transmission function. Below the twenty per cent point a significant reduction in slope was especially objectionable in the long-transmitting filters. Tables XV and XVI show the cut of each filter measured between the 2.5 and 50 per cent points, illustrating the extended bases of the spectral response curves. A typical example is shown in Figure 19.

Table XIII. Short-Transmitting Filters

Specification	Measured	Cut (mμ)
460	457	6
470	470	7
480	482	8
490	493	9
500	504	8
510	506	7
520	521	7
530	531	13
540	537	8
550	548	6
560	561	8
570	569	8
580	581	9
590	592	10
600	600	9
610	608	10
620	621	9
630	630	10
640	639	10
Average:		8.53

Table XIV. Long-Transmitting Filters

Specification	Measured	Cut (mμ)
460	461	13
470	474	13
480	483	15
490	486	13
500	497	13
510	509	13
520	522	22
530	536	23
540	544	25
550	553	19
560	564	19
570	568	22
580	583	20
590	595	24
600	603	28
610	612	29
620	622	26
630	630	27
640	640	28
Average		20.6

Table XV. Short-Transmitting Filters
2.5-to-50 Per Cent Cut

Wavelength	Cut (mμ)
460	11
470	12
480	13
490	12
500	14
510	14
520	11
530	27
540	14
550	14
560	13
570	15
580	17
590	15
600	15
610	15
620	15
630	18
640	18
Average:	14.90

Table XVI. Long-Transmitting Filters
2.5-to-50 Per Cent Cut

Wavelength	Cut (mμ)
460	20
470	21
480	22
490	21
500	23
510	24
520	35
530	39
540	38
550	31
560	34
570	35
580	33
590	37
600	41
610	42
620	39
630	40
640	45
Average:	32.63

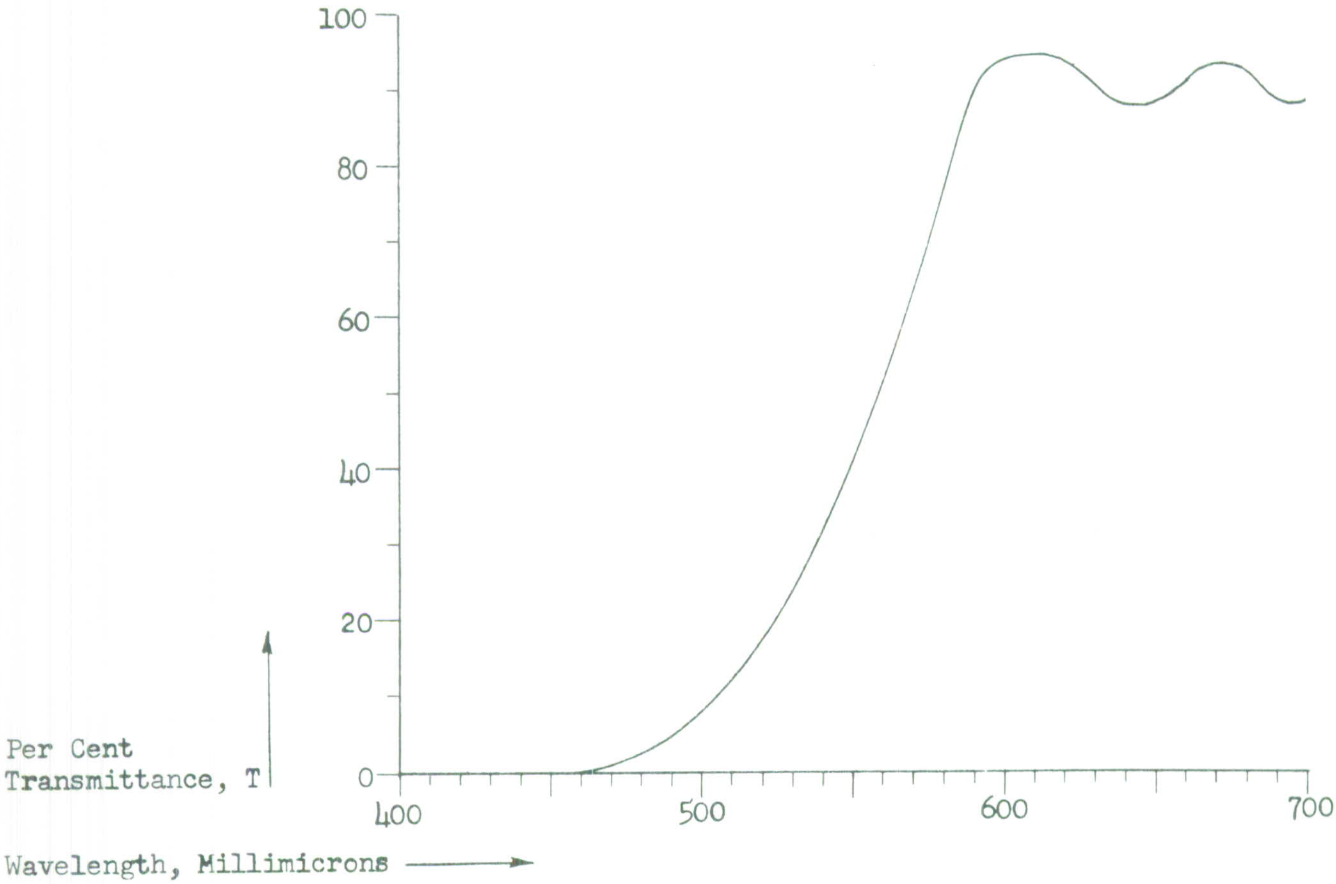

Figure 19. Typical long-wavelength-transmitting filter.

APPENDIX II

Additional Details of the Experimental Design and Procedures

In this experiment it was desired to determine visual detection thresholds in the presence of white ambient illumination and also in the presence of several different colored illuminants, each of which was equal in brightness to the white light. Using these data, it would then be possible to determine the amount of enhancement or depression of each Subject's detection threshold under each of the colored illuminants relative to this detection threshold for the same stimulus under the standard white illuminant.

As each Subject was to perform under every experimental condition it was important to balance, across Subjects, the order in which the conditions were experienced. Balancing was not complete, however, because complete balancing would have required many more Subjects than time and money allowed.

The number of Subjects used was 12, allowing two Latin Square replications of the sequence of six ambients in the detection threshold phase. To minimize the possibility of color adaptation anomalies and to use the experimental time as economically as possible, all threshold data to be collected under a particular ambient were collected before proceeding to the next ambient. Within ambients, the order of use of the several stimuli was balanced to the extent possible (Figure 20). No balancing was necessary for two of the ambients (A_1 and A_9) since only one stimulus was used with each. The A_5 condition, with three stimuli, was balanced by using each of the six possible orders of presentation for two subjects. For the A_3 and A_7 conditions, 12 of the 24 possible orders of four stimuli were used, such that each stimulus appeared equally often in each position and was followed equally often by each other stimulus. Under white illumination two Latin Squares determined the order of presentation of the five stimuli for ten of the Subjects; the other two Subjects were assigned two different orders, the net result being that each stimulus occurred in each position in the sequence either two or three times.

Similarly, in the brightness matching phase, each of the five colored ambient illuminants was used either two or three times in each position in the brightness matching sequence.

Brightness Matching

After the Subject had been seated for ten minutes, adapting to the colored light on the screen, the Experimenter read the following instructions over the intercom while operating the equipment as implied in the instructions:

S	BEGIN		ORDER OF THRESHOLD DETERMINATIONS			END
1	W: $S_5\ S_7\ S_3\ S_9\ S_1$ x	A3: $S_7\ S_3\ S_5\ S_1$	A7: $S_7\ S_5\ S_9\ S_3$ x	A5: $S_3\ S_5\ S_7$	A1: S_3	A9: S_7
2	A3: $S_5\ S_1\ S_7\ S_3$	A5: $S_7\ S_3\ S_5$ x	W: $S_1\ S_3\ S_9\ S_5\ S_7$	A9: S_7 x	A7: $S_7\ S_3\ S_5\ S_9$	A1: S_3
3	A7: $S_9\ S_3\ S_7\ S_5$ x	W: $S_9\ S_7\ S_1\ S_5\ S_3$	A1: S_3 x	A3: $S_5\ S_7\ S_3\ S_1$	A9: S_7	A5: $S_3\ S_7\ S_5$
4	A5: $S_3\ S_5\ S_7$	A9: S_7	A3: $S_1\ S_3\ S_7\ S_5$ x	A1: S_3	W: $S_1\ S_9\ S_3\ S_7\ S_5$ x	A7: $S_9\ S_5\ S_3\ S_7$
5	A1: S_3	A7: $S_7\ S_9\ S_3\ S_5$	A9: S_7 x	W: $S_3\ S_5\ S_1\ S_7\ S_9$ x	A5: $S_5\ S_7\ S_3$	A3: $S_3\ S_7\ S_1\ S_5$
6	A9: S_7	A1: S_3	A5: $S_7\ S_5\ S_3$ x	A7: $S_5\ S_3\ S_9\ S_7$	A3: $S_7\ S_1\ S_3\ S_5$ x	W: $S_7\ S_9\ S_5\ S_1\ S_3$
7	A9: S_7	A5: $S_7\ S_5\ S_3$	A3: $S_5\ S_3\ S_1\ S_7$ x	A7: $S_3\ S_7\ S_9\ S_5$ x	W: $S_5\ S_3\ S_7\ S_1\ S_9$	A1: S_3
8	A5: $S_5\ S_3\ S_7$	A7: $S_3\ S_7\ S_9\ S_5$	A9: S_7	A1: S_3 x	A3: $S_3\ S_5\ S_7\ S_1$ x	W: $S_9\ S_1\ S_7\ S_3\ S_5$
9	A3: $S_3\ S_1\ S_5\ S_7$	A9: S_7 x	W: $S_7\ S_5\ S_9\ S_3\ S_1$ x	A5: $S_7\ S_3\ S_5$	A1: S_3	A7: $S_5\ S_7\ S_3\ S_9$
10	A7: $S_9\ S_7\ S_5\ S_3$	A1: S_3	A5: $S_5\ S_3\ S_7$ x	W: $S_1\ S_7\ S_5\ S_9\ S_3$ x	A9: S_7	A3: $S_7\ S_5\ S_1\ S_3$
11	W: $S_3\ S_1\ S_5\ S_9\ S_7$ x	A3: $S_1\ S_5\ S_3\ S_7$	A1: S_3	A9: S_7 x	A7: $S_3\ S_5\ S_7\ S_9$	A5: $S_5\ S_7\ S_3$
12	A1: S_3	W: $S_3\ S_9\ S_7\ S_5\ S_1$ x	A7: $S_3\ S_9\ S_5\ S_7$ x	A3: $S_1\ S_7\ S_5\ S_3$	A5: $S_3\ S_7\ S_5$	A9: S_7

Figure 20. Order of use of ambient illuminants and stimuli in determining detection thresholds. W, A, S and x denote, respectively, white ambient, colored ambient, stimulus, and 10-minute rest period.

In this experiment we are gathering information about people's responses to various combinations of light. The information will be useful later in designing illumination systems for rooms in which people use cathode-ray tube displays.

The experiment will be done in two parts. In the first part we will ask you to adjust the brightness of the colored light falling on the screen you see before you. You can change its brightness by operating the control lever I have handed you. Try the lever. You will note that moving it right makes the screen brighter, and moving it left makes the screen darker. The color remains the same; only the brightness changes. You are to adjust the brightness of the color that is on the screen now until it matches the brightness of this (change) other color. In order to do this you will have to compare the two illuminants a number of times and make repeated fine adjustments until you are satisfied that the two are equally bright.

This will be our procedure. You are to remain seated looking at the screen. When I am ready to begin I will say, "start now." You will observe the screen brightness ... and, when ready for the other color, say "now;" whenever I hear you say "now" I will change (change) the color of the light. Whenever the adjustable light (show colored light) is on the screen you may either change its intensity or merely say "now" to get another look at the comparison light (show comparison light). When you are satisfied that the two lights are equally bright say "that's it." Then just continue to look at the screen until I again announce, "start now."

The objective is to make the two lights equally bright. We are in no hurry, so go back and forth as often as is necessary to achieve a good match. Do you have any questions?

The Subject made 13 brightness matches for each colored ambient, of which the last 12 were recorded. Between trials, with the light briefly removed from the screen, the Experimenter changed the brightness of the colored light by rotating the circular polarizer -20, -10, +10 or +20 degrees from the Subject's previous setting; the offset schedule was random, with the restriction that each of the four offsets be used three times.

Threshold Determination

After adaptation to the first ambient illuminant, the Experimenter read the following instructions over the intercom:

> Your task in this part of the experiment will be different than your task in the first part of the experiment. Note that the screen background is one color, and that on it there is a checkerboard pattern in a different color. This time the brightness of the checkerboard is adjustable. As before, moving the lever right increases brightness, moving it left decreases brightness. Try it. Your task is to adjust the checkerboard brightness until the checkerboard is just barely visible. To start each adjustment I will say "start now." You will then either decrease or increase the checkerboard brightness depending on whether or not you can see it. On each trial you may make as many up and down adjustments as you wish. When you are satisfied that the checkerboard is just barely visible, stop adjusting and say "now." A few seconds later I will announce the start of the next adjustment.
>
> Let's try it a few times. You now see a checkerboard. Adjust its brightness and inform me when you can just barely see it ... Now the checkerboard is too dim to be seen. Adjust its brightness again and inform me when you can just barely see it.
>
> Remember, on each trial you may make as many up and down adjustments as necessary to make the checkerboard just barely visible. Do you have any questions?

For each ambient-stimulus pair the Subject made 13 threshold adjustments, of which the last 12 were recorded. Between trials, with the stimulus path briefly occluded, the Experimenter changed stimulus brightness by rotating the circular polarizer -30, -20, +20 or +30 degrees from the Subject's previous setting; the offset schedule was random, with the restriction that each of the four offsets be used three times.

APPENDIX III

CALIBRATION PROCEDURES

Introduction

All optical equipment used in this study was calibrated in terms of the brightness measured at the screen, from the Subject's vantage point, using a Macbeth Illuminometer. All readings were made by the same operator, so that any brightness-matching bias which may have existed was applied equally to all conditions. The average of no less than five readings comprised each measurement, except in the case of preliminary data acquired for the purpose of standardizing optical components such as the rotatable polarizing discs; the average of no less than ten readings was taken for each point in the latter case. Standard procedure during the experiment was to make readings immediately before and after each subject's run, and to compute specific optical density (p. 22 ff) from the average of the before and after measurements. Calibration of individual units will be detailed below.

Dichroic Filters

The normal incidence spectral response of each dichroic filter, traced by an automatic recording spectrophotometer, was supplied by the manufacturer. Inasmuch as the angle of a skew ray through the devices was only four degrees, normal incidence data was considered to be sufficiently accurate. C.I.E. chromaticity coordinates of the filter pairs comprising each experimental stimulus and ambient were computed by the weighted-ordinate method[2] from the spectral data.

Stimulus and Ambient Filter Holders

These assemblies decreased the available screen intensity by (1) reducing the effective exit pupil of the projector optical system, and (2) absorption of the beamsplitter in the ambient filter holder. The first effect was of concern only to the extent that it might change during the course of a run due to careless operation. Measurements at the screen indicated that movement along the optical axis of up to three inches did not result in a measurable decrease in brightness, whereas the mount was so designed that it could be completely disassembled

and reassembled (in order, for instance, to replace a burned-out projector lamp) with a maximum error along this axis of one half-inch. Movement transverse to the optical axis sufficient to reduce screen brightness resulted in reflection of the interrupted part of the beam into the operator's eyes, and was thus immediately apparent and correctable.

Absorption of the aluminized beamsplitter was determined to be insensitive to reflectance angle within the rotational limits of the mount. A measured difference in brightness between the reflected and transmitted beams amounting to an optical density of 0.4 in the reflected path was compensated for by inserting a 0.4 netural density filter in the transmitted path, in order that the long- and short- wavelength amplitudes of the ambient spectra should be equal.

Uniformity of screen illumination was measured with all optical components except the colored filters in place. Corner-to-center uniformity is shown below in optical density referred to center brightness (differences in uniformity within the area of the stimulus image were not measurable):

0.05		0.10
	0.00	
0.12		0.10

Rotatable Polarizing Discs

The motor-driven disc and the manually-set polarizer were both calibrated in the same manner. With a scale in degrees cemented to the movable member, the device was inserted in the projector beam, and brightness measurements were made at the screen for ten-degree angular increments of the polarizer. Average brightness readings at each position were then converted to density, and a calibration curve was drawn of density versus angle. Finally, a density scale was inscribed on the movable polarizer, so that experimental data could be transcribed directly in terms of this variable.

Projectors

Two Graflex S-100 slide projectors, with 500-watt tungsten lamps, served as light sources for this experiment. Mains voltage was monitored before and after each run to guard against a resultant change in color temperature, although this would have had at most a second-order effect on observable color. No change in voltage was recorded at any time during the course of the study.

By an uncommon run of luck, no projector burnouts occurred during actual runs. Both lamps were replaced whenever one failed, and new lamp pairs were energized for one hour before proceeding with data collection.

APPENDIX IV

ANALYSIS OF VARIANCE FOR COLORED-WHITE AMBIENT MATCH

Source of Variation	df	SS	MS	f
Within Subjects	132	0.3735	0.00283	
Between Subjects	11	2.2831	0.2076	73.36*
Total Subjects	143	2.6566	0.01858	
Ambients	4	93,8517	23.4629	7,820.97*
Ambients x Subjects	44	2.4452	0.0556	15.74*
Pooled Trials, Interactions	528	1.8629	0.00353	

*Significant at $p < 0.005$

APPENDIX V

ANALYSIS OF VARIANCE - CENTRAL SUBSET

Source of Variation	df	SS	MS	f
Stimulus	2	0.3718	0.1859	64.10**
Ambient	3	0.1321	0.0440	15.17**
Subjects	11	3.5495	0.3227	111.28**
Stimulus x Ambient	6	0.0165	0.0029	1.00
Stimulus x Subjects	22	0.1423	0.0065	2.24*
Ambient x Subjects	33	0.5781	0.0175	6.03**
Stimulus x Ambient x Subjects	66	0.1913	0.0029	
Totals	143	4.9816		

*Significant at $p < 0.01$

**Significant at $p < 0.005$

APPENDIX VI

ANALYSIS OF VARIANCE FOR RELATIONAL PARAMETERS VERSUS STIMULI

Source of Variation	df	SS	MS	f
Relational	2	0.0919	0.0460	5.69**
Stimulus	2	0.0594	0.0295	3.65*
Subjects	11	1.0633	0.0967	11.97**
Relational x Subject	22	0.1317	0.0059	---
Stimulus x Subject	22	0.2200	0.0100	1.24
Relational x Stimulus	4	0.0226	0.0057	---
Relational x Subject x Stimulus	44	0.3554	0.00808	
Totals	107	1.9443		

*Significant at $p < 0.05$

**Significant at $p < 0.01$

APPENDIX VII

ANALYSIS OF VARIANCE FOR RELATIONAL PARAMETERS VERSUS AMBIENTS

Source of Variation	df	SS	MS	f
Relational	2	0.0069	0.00345	
Ambient	2	0.1352	0.0676	10.2*
Subjects	11	1.3300	0.1209	18.2*
Relational x Subject	22	0.1349	0.0061	
Ambient x Subject	22	0.3547	0.0161	2.42*
Relational x Ambient	4	0.0318	0.00795	
Relational x Subject x Ambient	44	0.2925	0.0665	
Totals	107	2.2860		

*Significant at $p < 0.01$

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An illumination system is described which utilizes for display, portions of the visible spectrum which have been excluded from the ambient light. The resulting tinted illumination is matched in brightness to a standard white light by experimental subjects, and stimulus threshold measurements made as a function of display intensity for various stimulus and ambient spectra. Certain combinations are found to lower the threshold of detection, indicating enhanced stimulus brightness, whereas others are found to raise the threshold. A close relationship is found between experimental data and results predicted on the basis of previously published increment-threshold measurements.

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